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The Effect Of Ship Inherent Controllability On Piloted Performance: Evaluation And Prediction

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16. Abstract

This report describes the development of statistical formulas relating ship controllability indices to measures of piloted performance. These formulas contribute to a methodology for the evaluation or prediction of risk in a waterway from the characteristics of user traffic.

Data for this development were provided by a simulator experiment described in a previously published report entitled, "The Effect of Ship Inherent Controllability on Piloted Performance: The Simulator Experiment," by M.W. Smith, J. Mazurkiewicz, and W.K. Brown, CG-D-10-90/AD-A 228968. During this experiment, seven commercial ships, ranging in size from 33,000 to 250,000 deadweight tons made multiple runs through narrow channels under comparable conditions.

The analysis reported here found that the means and standard deviations of the crosstrack distances required as a function of ship characteristics were best predicted in the immediate turn by the tactical diameter, and in other maneuvering regions by Nomoto's indices, T and K.

The application of the new procedures to the U.S. Coast Guard's waterway design process is discussed. The process will be more accurate and versatile, but results will not be comparable to previously existing evaluations. (See Waterway Design Manual, M.W. Smith, CG-D-18-92/AD-A 257030.)

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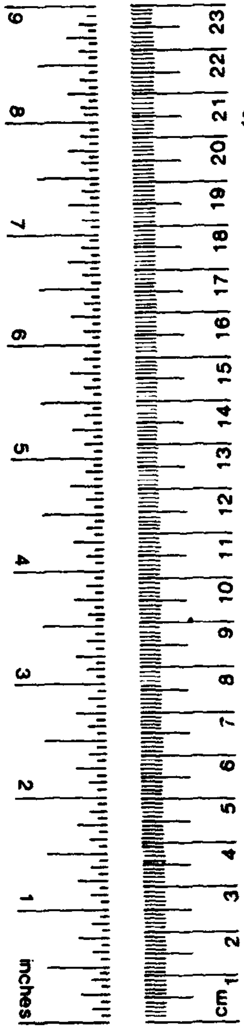
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

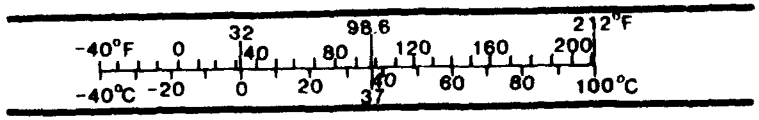
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly).



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



EXECUTIVE SUMMARY

INTRODUCTION

The United States Coast Guard (USCG) uses an evaluation procedure to support the design and management of waterways (USCG Aids to Navigation Manual-Administration COMMANDANT INSTRUCTION M16500.7, CG-D-18-85). The procedure provides a quantitative measure of performance, or risk, for specified conditions, including waterway configuration, aids to navigation, environmental conditions, and the characteristics of user traffic. In recent years, the sizes of commercial ships have increased with correspondingly-greater risk. To respond to these changing conditions and to anticipate a continuation of this trend, the USCG has conducted a study to increase the range of ship sizes that can be treated by the evaluation procedure and to improve the accuracy of the treatment.

APPROACH

The original evaluative procedure was based on performance data taken from a series of real-time man-in-the-loop simulator experiments, which used sophisticated ship models, standard waterway conditions, and licensed commercial pilots. To provide additional performance data, a new simulator experiment was conducted at the USCG Academy in New London, Connecticut. This experiment tested seven (7) large, commercial ships, which were selected to vary along a number of physical dimensions and indices of inherent controllability. The experiment is described in detail in a separate report (CG-D-10-90). The present report describes an analysis of these data to develop regression formulas relating ship inherent controllability and piloted performance for ships from 33,000 to 250,000 deadweight tons. These formulas are being incorporated in a revision of the evaluation procedure expected in 1991.

Because of the complexity of the problem and the general novelty of the approach, little direct guidance was available in the literature and every step of the analysis required the development of appropriate methods. The conclusions that follow are divided into sections on the selection of the ship parameters, the measurement of piloted performance, and the development of the regression formulas, but the division is entirely arbitrary. Conclusions about each component are based on its effectiveness in functioning with the others.

CONCLUSIONS

The first and most obvious step in the **selection of ship parameters** was the consideration of physical dimensions, length, beam, draft, and displacement, that would be easily available to USCG users of the final evaluation procedure. Unfortunately, these were only modestly effective in describing piloted performance. Major consideration was given to parameters derived from the most common sea trials, or "standard maneuvers"--the turning circle and the zigzag maneuver. The specific "indices of ship inherent controllability" considered were the following: tactical diameter, overshoot angle, time to reach the first execute heading change, course lag time, K and T (Nomoto's indices), and P (Norrbin's index). The final selection among these indices was based on their effectiveness in the development of the regression formulas.

During the **measurement of piloted performance**, representative data were selected from the recorded experimental transits. The waterway was divided into "regions" based on the required ship maneuver (for example, a turn). The transits were examined for the most common piloting technique in each region: that is, a characteristic pattern of crosstrack position, heading, and rudder angle. For each maneuvering region, in each transit, the point of greatest "risk," or closest approach of the ship's extreme point to the channel edge, in performing that maneuver was identified. There, the crosstrack distance of the ship's center of gravity from the centerline was selected for inclusion in the data sample representing that region. The means and standard deviations of these crosstrack distances proved quite sensitive to indices of inherent controllability.

During the **development of the regression formulas,** a number of models forms were considered, each based on one or two indices. To be selected, a specific model had to correlate very highly with piloted performance data and the index or indices on which the model was based had to be meaningful for the requirements of the subject maneuvering region. The summary of the final selections follows:

1. The tactical diameter was a superior index in the turn region where a steady hard rudder deflection is required. Linear relations between the tactical diameter and the mean and/or standard deviation were determined.

2. K, an index of turning ability, and T, an index of quickness of response to steering, were the most effective in those regions where the rudder is used dynamically. Linear models of relations between K and T and the mean and/or standard deviation were selected in the turn-recovery, recovery, and entry regions.

3. The ship's beam was used as a parameter in the trackkeeping regions where piloted performance was not strongly related to inherent controllability.

A complete set of final regression formulas is presented in Section 4.

RECOMMENDATIONS

The new formulas are to be implemented in a revision of the evaluation procedure. The recommended form and anticipated consequences of this implementation are discussed in the final section. As intended, the revised procedure will be able to evaluate the contributions of a range of ship sizes up to the largest that might possibly be accommodated in restricted waterways. The new evaluations will be more accurate and, therefore, do not need the substantial "conservatism," or over-estimation of risk, that was built into the original procedure. Relatively more realistic estimates of risk should enhance confidence in the procedure. Note that the differences are sufficiently great that evaluations done with old and new versions cannot be directly compared.

Other recommendations are made. To maximize the usefulness of the evaluation procedure, the supporting software contains routines that use easily-available physical parameters to estimate less-easily-available indices of inherent controllability. These routines could be developed further to increase accuracy. Other potential applications for the new regression formulas are suggested: in the training of shiphandlers and in the design of steering displays. The analysis process that has been advanced here could be applied to further data on additional aspects of the restricted waterway situation. Additional conditions suggested for further evaluation include the alongtrack distance needed for a maneuver, the effect of channel width on risk, and the performance of ballasted tankers in the presence of wind.

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1.0 INTRODUCTION

1.1 SHIP PERFORMANCE IN RESTRICTED WATERWAYS

The United States Coast Guard (USCG) uses an evaluation procedure to support the design and management of waterways (USCG Aids to Navigation Manual-Administration COMMANDANT INSTRUCTION M16500.7; Smith, Marino, and Multer, 1985). The procedure provides a measure, the relative risk factor (RRF), to quantify the performance or risk in a waterway, given knowledge of the waterway configuration (including the aids to navigation), the user traffic, and the environmental conditions. The present report describes a major revision to an important component of the procedure--the treatment of user traffic.

The sizes of commercial ships have increased in recent years and larger ships, with their correspondingly-greater risk, are becoming more common in restricted waterways. The procedure presently being used by the USCG is accurate for estimating risk in waterways with only moderate-sized ships. In order to respond to the changes in user traffic, the USCG needed to revise its evaluation procedure to accurately estimate performance with ships as large as 225,000 deadweight tons (dwt). Piloted performance data on ships to this size were collected in a simulator experiment reported separately (Smith, Mazurkiewicz, and Brown, 1990). The present report describes an analysis of these data to relate ship inherent controllability and piloted performance for ships from 33,000 to 250,000 dwt. This relation will be implemented in a revision of the evaluation procedure expected in 1991 (Smith, Mazurkiewicz, and Smith, in preparation).

1.2 BACKGROUND

Earlier phases of the USCG Waterway Performance, Design and Evaluation Project have also included analyses of the contribution of ship characteristics to performance in restricted waterway. In earlier experiments, the performance of three sizes of tankers from 30,000 to 80,000 deadweight tons (dwt) were evaluated (Bertsche, Atkins, and Smith, 1981; Marino, Smith, and Moynehan, 1984). Performance data from these experiments were used to develop a "ship size correction factor" based on deadweight tonnage (Bertsche, Smith, Marino, and Cooper, 1982; Smith et al., 1985) that allowed generalization to ships differing in size from those used in the data collections. While this correction factor was appropriate for relatively-similar tankers over a relatively-narrow range of sizes, it was not appropriate for a greater variety of ships or a much broader range of ship sizes. The new procedure is intended to replace it and to provide a much more versatile tool.

Another USCG-sponsored study provided an important resource to

the present effort (Barr, Miller, Ankudinov, and Lee, 1981; Landsburg et al., 1983; NKF Engineering, 1989). In support of a program to set maneuvering performance standards for large, commercial ships, a computer data base was developed to contain information on ship types, physical characteristics, and maneuvering performance. The database was used to relate measures of maneuvering performance to physical ship parameters and to provide statistical summaries of observed maneuvering performance. For the present analysis this earlier work provided a relatively-large sample of commercial ships against which to compare the smaller sample of experimental ships and helped guide the selection of the ship indices that might prove most effective. The use of this related work in the design of the supporting experiment is described in the accompanying report (Smith et al., 1990). The use of the Barr study is described again the present report in Section 2.

1.3 OBJECTIVE AND SCOPE OF THE PRESENT EFFORT

The objective of the present effort was the development of statistical formulas that relate measures of observed piloted performance to parameters of ship characteristics and to use these formulas to predict future performance. The formulas developed can be expressed in their most general form as follows:

Performance Measure = f(Inherent Controllability Indices), with other factors constant (1)

where: f ( ) is a general notation for a function of independent variables placed in parenthesis. The scope of the effort was to select the performance measures and the indices of inherent controllability, and to develop the specific forms of this formula.

A literature search led to the following general conclusions about the "state of the art:"

- Among the investigations of ship inherent controllability conducted in many countries, there are no commonly-accepted indices of shiphandling qualities.
- Among the studies that have been done on piloted performance, or risk, in restricted waterways, there is no quantitative measure that would be commonly accepted.
- In the reviewed literature, no quantitative relation between inherent controllability and piloted performance has yet been proposed.

Because of this relative lack of guidance, a considerable amount of effort was necessary to select the most effective parameters and to develop the methodology to solve the present problem. A number of indices of ship inherent controllability were selected from the literature and examined to determine their

potential and actual effectiveness in the present context. Measures of piloted performance used in earlier phases of the Waterway Performance Study were subjected to new procedures to enhance their representation of observed performance. Regression models were selected to express the observed relation between ship inherent controllability and piloted performance. Descriptions of these processes comprise much of this report.

1.4 THE SUPPORTING SIMULATOR EXPERIMENT

A simulator experiment was designed and conducted to provide the appropriate piloted performance data. This experiment is described in some detail in a separate report (Smith et al., 1990), but a brief overview of the important features is presented here as a convenience to the reader.

1.4.1 Ships and Ship Parameters

The seven "ships" were selected to meet a number of criteria. They covered the range from 33,000 to 250,000 dwt, with special attention to 150,000 dwt. In keeping with the context of the Waterway Project, all ships were of a size and type that would confine them to a dredged channel in restricted waterways and that would require a licensed, commercial pilot. Because the intended data analysis required that they be meaningfully described by common parameters, they all had conventional hulls and were allowed no external maneuvering assistance. The physical dimensions considered in the selection of the ships included displacement in long tons, length between perpendiculars, beam, and draft. Parameters of controllability considered in their selection included a nondimensional tactical diameter calculated from the turning circle, and Nomoto parameters, steering quality indices, calculated from zigzag maneuvers. The final ships included a 33,000 dwt bulk carrier, a 1000-foot Great Lakes ore carrier, a 76,000 dwt bulk carrier, three versions of a 150,000 dwt bulk carrier (varying in rudder effectiveness), and a 250,000 dwt tanker.

1.4.2 Design and Conduct of the Experiment

To meet the experimental objective of measuring the contribution of the ship to over-all performance in restricted waterways, it was necessary to design an appropriate context of waterway and piloting conditions. All ships were run in a narrow channel, outlined by buoys, with a single 35· turn to the left. To add a realistic level of difficulty, there was a wind and current that varied within the run (but was the same between runs). Because the ships varied so much in size, the width of the channel was adjusted to each ship. Because channel width is a critical factor in the risk represented by ship size or controllability, channel width was treated as an experimental variable by running one mid-sized ship

in three different widths of channel. Commercial pilots, experienced with the particular ship size, each made multiple runs with the ships assigned to him. In all, 16 runs were made with each of the seven ships. The mid-sized ship was run eight times in each of two additional widths of channel.

In anticipation of the planned analysis that would look for a dependence of the piloted maneuvers on the inherent controllability of the ships, the transit conditions and pilot instructions were planned to sample the maneuvers needed in a narrow channel. Each run was initialized with the ship to the right of the channel with its heading equal to the course of the channel, approximately two nautical miles below the single turn. The pilot was instructed to bring the ship to the centerline, to trackkeep until preparation for the turn, to make the turn by his own strategy, to bring the ship back to the centerline of the new leg, and to trackkeep again with a different wind and current until the end of the run. These component maneuvers played an important part in the results and analysis.

1.4.3 Preliminary Analysis and Results

The analyses were begun using the techniques that are the bases of the SRA/RA Systems Design Manual's quantitative procedures (Smith et al., 1985). Group performance for a particular ship was represented by the crosstrack distribution of the 16 ship tracks over the length of the transit. The first examination concentrated on the most difficult and highest risk regions, the turn and turn-recovery. In these regions, there was a straightforward relation between ship size (displacement in long tons) and crosstrack distance from the centerline, but there was no obvious relation between inherent controllability and distance. It was concluded that earlier methods of data analysis were not adequate to analyze these new data and other methods were explored. Examination of the data for each individual pilot showed occasional runs with tracks sufficiently different as to interfere with a simple relation between ship characteristics and the grouped tracks. For maximum representation of the observed performance, the data analysis was taken down to the level of the individual run. This more-extensive data analysis is described in the present report.

1.5 OVERVIEW OF THIS REPORT

Section 2 INDICES OF SHIP INHERENT CONTROLLABILITY describes the review of the literature on indices of inherent controllability and the selection of a set of indices for further consideration in the development of the formulas.

Section 3 MEASUREMENT OF SHIP PILOTED PERFORMANCE describes the measures of piloted performance adapted from earlier phases of the Project, the selection of representative values for each

"maneuvering region," and the adjustment of these values for channel width.

Section 4 DEVELOPMENT OF THE REGRESSION MODELS is the principal results section. It describes the selection of the model forms, final selection of indices of controllability, and the complete set of final formulas.

Section 5 CONCLUSIONS AND RECOMMENDATIONS presents conclusions about the measurement of piloted performance, the development of the regression models, the final selection of indices of ship inherent controllability, and recommendations about potential applications and extensions of these findings.

Section 6 APPLICATION TO THE WATERWAY DESIGN MANUAL is very specific to the USCG requirement, discussing the implications of the new findings for that primary user group.

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2.0 INDICES OF CONTROLLABILITY

2.1 CONSIDERATION OF THE LITERATURE

Most of the studies which give a modern treatment of the ship's handling qualities were published after the year 1940. The first papers which appear to be pertinent are Kempf's paper entitled "Maneuvering Standards of Ships" (1944) and Davidson and Schiff's "Turning and Course-Keeping Qualities" (1946). Since that time, investigations have been conducted in many countries to establish criteria for evaluation of ship's controllability and to develop the most integrated description for it (Crane, 1979; Della Loggia et al., 1977; Gertler and Gover, 1960; Gill, 1979; Nomoto et al., 1957; Nomoto and Norrbin, 1969; Panel H-10, SNAME, 1975). In spite of impressive efforts and important achievements, there are as yet no commonly-accepted indices of the ship's handling qualities. This lack can be explained by the complexity of shiphandling. However, an increasing number of partial descriptions and criteria have been developed. The large number leads to a multi-index classification of the ships, like a method proposed by Glansdorp (Landsburg et al., 1983) that involved results from 20 possible maneuvering trials. Such an approach appears to be too complex for practical use. Many of the maneuvers involve similar modes of performance, but consideration of too few maneuvers can cause some important handling qualities to be overlooked (Abkowitz, 1980; Crane, 1979; Gertler and Glover, 1960; Landsburg et al., 1983; Nizery, 1975). Thus, the present problem is to establish the smallest set of maneuvering trials and resulting indices which will describe the ship's inherent controllability with acceptable accuracy and discrimination.

To be consistent with existing literature, two definitions have been adopted in this study. "Controllability" defines a vessel's ability to maneuver and also to maintain or correct course, speed, and/or position. The adjective "inherent" emphasizes the qualities which are built into a ship, without consideration of the capabilities of the shiphandler (Barr, 1987; Landsburg et al., 1983). The emphasis of this study is on selected aspects of the inherent controllability related to normal transit of a waterway. It includes turning and checking (course-changing) abilities.

Potential indices for this study were selected from the literature with the criteria that each has a unique value for a specific ship, discriminates among ships representing different qualities, and is routinely-available for an existing ship. The selection of the final set was based on their usefulness as independent variables for formulas based on the experimental data. This approach is similar to that used in the USCG's "Technical Basis for Maneuvering Standards" (Barr et al., 1981).

An important group of controllability indices used in ship

design does not satisfy the criterion of being routinely-available. These are the indices calculated from the equation of ship's motion (Comstock, 1967; Davidson and Schiff, 1946; Goodman et al., 1976; Roseman et al., 1987). Unfortunately, the ship's mathematical model cannot be expected to be a part of the routinely-available data for any existing ship. Despite the demonstrated effectiveness of these indices in ship design, they were not included here in the consideration of potential indices.

One type of controllability indices available for a majority of existing ships is that that can be extracted from sea trial data. Typical ship's trials consist of "standard definitive maneuvers," which have been designed for the identification of a ship's maneuvering performance. There is reasonable expectation that data from at least the "main" standard maneuvers would be available for the first ship of a class (Landsburg et al., 1983). Consequently, indices based on the standard definitive maneuvers were included for consideration here.

Standardization of the definitive maneuvers has not yet been completed. However, at least four respected organizations have developed maneuvering trial codes. Table 1 shows that the Society of Naval Architects and Marine Engineers (SNAME), the International Towing Tank Conference (ITTC), the British Ship Research Association (BSRA) and Det norske Veritas (DNV) all agree ("Code," SNAME, 1973; "Code," BRSA, 1972; Nizery, 1975; "Rules, DNV, 1986) in their trial codes on the need for three particular maneuvers: turning circle from "full" speed ahead, Kempf's zigzag maneuver, and crash-stop from "full" speed ahead. Three of them also include the spiral maneuver. This comparative list can be extended to include maneuvers used by the U. S. Coast Guard in the "Technical Basis for Maneuvering Performance Standards" (Barr, 1987), the Maritime Administration (MARAD) in the "MARAD Systematic Series of Full-form Ship Models" (Roseman et al., 1987), and the International Maritime Organization in the "Draft Guide lines for Considering Maneuvering Performance in Ship Design" ("Draft Guidelines," IMO, 1983). The recommended maneuvers are summarized in Table 1. There, one asterisk indicates that the test is recommended by the organization; two, that it is very strongly recommended. The asterisks are summed in the last column of the table as an indication of the overall relative importance given to each test. According to the table, the turning circle and Kempf's zigzag maneuver are the most commonly-recommended standards. They determine the ship's turning and course-changing abilities with acceptable accuracy. (The crash stop is not included in the data taken from the simulator experiment.)

A comparative methodology can be employed again for the selection of parameters which have been derived from the above standard definitive maneuvers, and which are recommended as indicators of

TABLE 1. RECOMMENDED MANEUVERING TRIALS

MANEUVER	Principal Maneuvering Trial Codes				USCG	Mar.Ad	IMO	Total
	SNAME	ITTC	BSRA	DnV				
Turning test	*	*	*	*	*	*	*	7
At full speed	*	*	*	*		*		5
At medium speed		*			*	*	*	4
At slow speed		*	*	*				3
With propulsion stopped				*				1
From zero speed		*	*	*				3
Zigzag maneuver	*	*	*	*	*	*	*	7
-20 deg / 20 deg	*	*	*		*	*	*	6
-10 deg / 10 deg		*	*	*		*	*	5
Pullout (from turn)		*	*	*			*	4
Weave maneuver			*					1
Direct spiral		*	*			*	*	4
Reverse spiral		*	*	*			*	4
Statistical method			*					1
Change of heading		*					*	2
Crash-stop	*	*	*	*	*	*	*	7

the inherent controllability qualities. Parameters listed in the MARAD Systematic Series of Full-form Ship Models are the widest group taken into consideration in this study. That set of the potential indices is compared in Table 2 and Table 3 against: M. Gertler and S. C. Gover's suggestions in the "Handling Quality Criteria for Surface Ships" at the First Symposium on Ship Maneuverability (Gertler and Gover, 1960), U.S. Coast Guard's Maneuvering Performance Standards (Barr, 1987; Barr et al., 1981; Barr et al., 1989), parameters used at Hydronautics, Inc. for surface ship maneuvering predictions (Goodman et al., 1976), and parameters recommended by ITTC (Nizery, 1975).

As shown in Table 2, all sources agree that geometrical parameters of the turning circle (the tactical diameter, the advance, and the transfer) are the numerical measures of primary interest. It has been determined in statistical analysis of maneuvering trial data that the advance, the transfer, and the tactical diameter are closely related and, thus, only one of these measures is needed to characterize turning performance (Landsburg

TABLE 2. RECOMMENDED PARAMETERS FROM THE TURNING CIRCLE MANEUVER

TURNING CIRCLE	MARAD Syst. Series	Handling Quality Criteria	Maneu-vering Perfor-mance Standards	Shipboard Maneuver-ing Data;	Ship Maneu-vering Predic-tions;		Total
Parameters	Mari-time Admin.	Gertler ,Gover	U.S.Coast Guard	Fifth STAR Symposium	Hydro-nautics	ITTC	
Time to change heading 90 deg.	*	**			**	*	6
Time to change heading 180 deg.	*	**			**	*	6
Speed loss	*	**	•		**	*	6
Advance	*	**	*	*	**	*	8
Transfer	*	**	*	*	**	*	8
Tactical Diameter	*	**	**	*	**	*	9
Steady turning Diameter	*			*	**	*	5

et al., 1983). The nondimensional tactical diameter is the most widely used as the index. That conclusion confirms Davidson's proposal of using the numerical ratio $(D/L)_{min}$ as an index of turning ability (Davidson and Schiff, 1946). In addition, the tactical diameter is practically independent of the ship's speed for full forms and low Froude numbers (Abkowitz, 1980; Crane, 1979; Eda et al., 1979). The dependency of the tactical diameter on the rudder deflection can be partially neutralized by the use of a tactical diameter transformed to the 35-degree rudder deflection (Barr et al., 1981, Barr et al., 1989; Landsburg et al.,1983) as follows:

$$D^*_T = D_T \cdot 35^\circ / \delta_R \cdot L \qquad (2)$$

where: D_T is the tactical diameter determined for δ_R rudder deflection, D^*_T is the nondimensional tactical diameter, and L is the ship length between perpendiculars.

Table 3 demonstrates a general agreement that the first overshoot angle and the time to reach the first execute heading change (Figure 1) are the primary numerical measures to be obtained from the zigzag maneuver. The first overshoot angle is used

TABLE 3. RECOMMENDED PARAMETERS FROM KEMPF'S ZIGZAG MANEUVER

KEMPF' ZIGZAG	MARAD Syst. Series	Handling Quality Criteria	Maneu-vering Perfor-mance Standards	Shipboard Maneuver-ing Data;	Ship Maneu-vering Predic-tions;		Total
Parameters	Mari-time Admin.	Gertler ,Gover	U.S.Coast Guard	Fifth STAR Symposium	Hydro-nautics	ITTC	
Time to reach exec heading change	*	**			**	*	6
Overshoot angle	*	**	**	*	**	*	9
Width of path at first execute	*						1
Overshoot width of path	*				**		3
Total width of path	*						1
Reach	*	*			*	*	4
Second overshoot heading angle	*						1
Third overshoot heading angle	*						1
Period	*	*			*	*	4
OTHERS			K', T'				1

typically as a measure of the course-checking/course-keeping abilities. The time to reach the first execute heading change is a direct measure of ability to rapidly initiate changes in course.

The reach time and the period are more significant for frequency response analyses than for identification of handling qualities (Goodman et al., 1976). The path-width data, like the path-width overshoots, require elaborate instrumentation on ship trials and therefore are seldom obtained for real ships (Goodman et al., 1976). The second overshoot and the third overshoot angles are important supporting parameters in evaluation of the ship's inherent instability (Roseman et al., 1987), but they are not used as frequently in describing the ship's handling qualities as the data derived from the first overshoot.

The first overshoot angle and the time to reach the first ex-

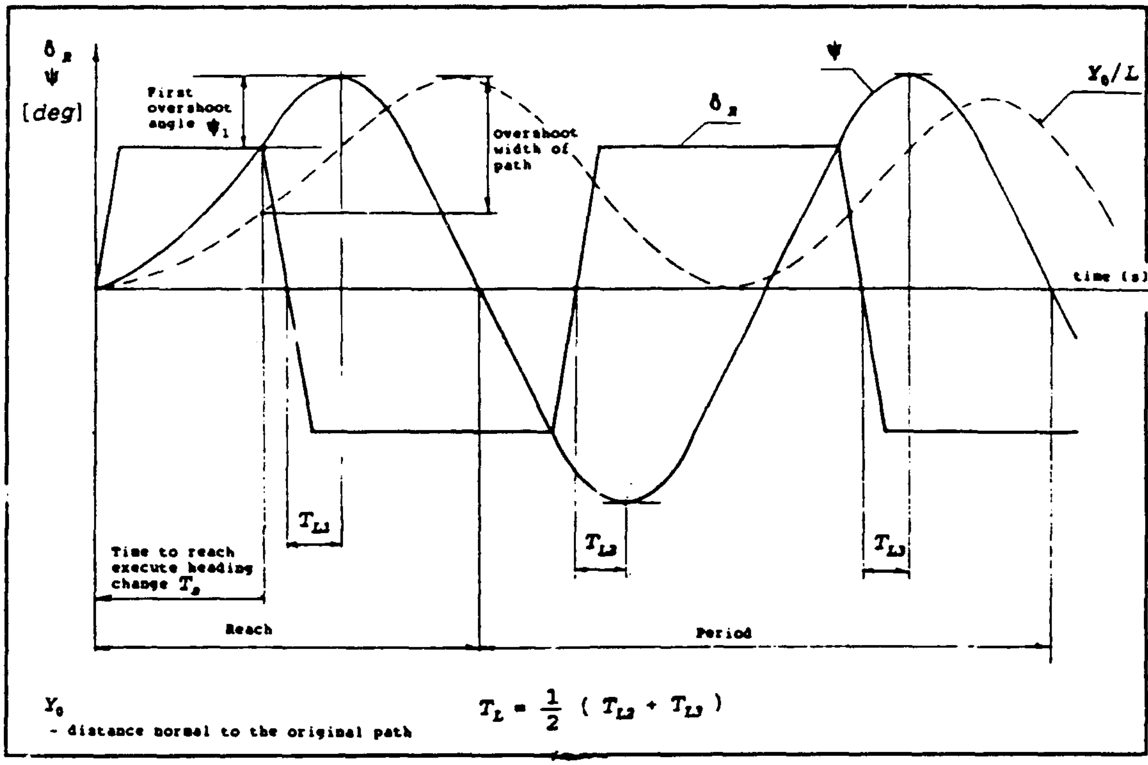

FIGURE 1. KEMPF'S ZIGZAG MANEUVER

ecute heading change have some disadvantages as potential indices of inherent controllability. The first overshoot angle varies with the rudder deflection; however, it is approximately independent of the ship's speed. The time to reach the first execute heading change varies with the ship's speed, but its sensitivity to the rudder deflection is negligible. Those disadvantages can be partially neutralized using the approach already adopted for the tactical diameter. The potential indices can be defined as follows:

$$(\Delta\Psi_1)_{index} = \Delta\Psi_1 \cdot 10 / |\delta_R| + |\delta_R| / 10 - 1 \tag{3}$$

$$(t_a)_{index} = t_a \cdot U_0 / 8 \tag{4}$$

where: $\Delta\Psi_1$ is the first overshoot angle, δ_R is a rudder deflection in degrees, t_a is the time to reach the first execute heading change, and U_0 is an approach speed in knots.

The overshoot angle has an additional weak point as a potential index. It cannot discriminate a ship with good turning ability and quick response to the reversed rudder from another one with poor turning ability and slow response (Nomoto, 1966; Nomoto and Norrbin, 1969). This weakness means that the overshoot angle must be used together with another index that represents quickness of response: for example, with the time to reach the first execute heading change.

It is shown in Table 3 that The Ship Maneuvering Data Base, developed by the U. S. Coast Guard, also includes the so-called Nomoto-Norrbin indices (Barr, 1987; Barr et al., 1989). They present an alternative approach which is also based on the zigzag maneuver data. The approach was presented by K. Nomoto at the First Symposium on Ship Maneuverability in 1960 (Nomoto, 1966). Since that time it has been extensively examined, improved, and discussed by Nomoto, Norrbin, and others (Amerongen, 1984; Asinovsky, 1983; Barr, 1987; Van Berlekom and Goddard, 1972; Della Loggia et al., 1977; Hess, 1977; Landsburg et al., 1983; Laredo et al., 1977; Narita et al., 1974; Nomoto, 1966; Nomoto et al, 1957; Nomoto and Norrbin, 1969; Nomoto, 1977). It still remains controversial. A short review of Nomoto's idea and discussion of selected qualities of the indices are presented below.

Nomoto assumed that motion of a ship in steering can be fairly-well described by a first order equation of "equivalent" yaw motion as follows:

$$T \cdot dr/dt + r = K \cdot \delta_R \quad (5)$$

where: T is a time constant, $r = d\Psi/dt$ is an angular turning velocity of a ship, Ψ is a heading angle of a ship, t is time, K is a gain, and δ_R is a helm angle.

Equation (5) is commonly used in the theory of dynamics of physical systems for the description of forced motion of linear systems (Cannon, 1967). K and T are known as Nomoto indices.

Coefficient K indicates a final turning rate of a ship for a given helm angle. The larger the value of K, the greater is the final turning rate of a ship, and, the smaller is her steady turning circle. Consequently, K represents the turning ability of a ship. The rapidity with which a ship approaches the final turning rate is defined by the index T. The smaller the T value, the more quickly the angular motion of a ship builds. Thus, T can represent the quickness of response to steering.

The index T can also represent stability on course, which is a vessel's ability to return to a steady course (or to the initial turning condition) with controls fixed, after the vessel was disturbed by transient external force. The smaller the T value, the

more stable is the ship on course, because the quicker is the decay of the heading deviation rate. Thus the stability on course agrees with the quick response to steering. Consequently, T is an index of both. More generally, T can be treated as an index of course-keeping ability, which is a vessel's ability to keep a course actively but easily on a seaway.

Nomoto proposed nondimensional forms for the indices as follows:

$$K^* = K \cdot L/U \tag{6}$$

$$T^* = T \cdot U/L \tag{7}$$

where: K^* and T^* are nondimensional indices, L is the ship's length between perpendiculars, and U is the ship's speed.

Definitions (6) and (7) suggest that indices should have constant values for a specific ship. Unfortunately, they vary significantly with the helm angles. That variation has been considered a result of the so-called nonlinear effect in steering quality (Amerongen, 1984; Nomoto, 1960). Thus, to be consistent for different ships, the indices must be determined for a unified helm angle. Also, the "linear on the average" concept has been proposed by Nomoto and Norrbin (Nomoto and Norrbin, 1969).

Values of K^* and T^* can be calculated from the zigzag maneuver data using a procedure recommended by Nomoto (Nomoto, 1960). The fundamental assumption in the procedure is that correct values of K and T are those with which the Equation (5) can describe the ship motion observed in the maneuver. Comparison of the original zigzag maneuver against its approximation by the associated linear model can provide information as to the reliability of the crucial assumption that the linear model represented by Equation (5) can describe ship motion fairly well. Published results of such analyses confirm the commonly-accepted fact that the linear theory fails to predict accurately the characteristics of the tight maneuvers and that it is especially inadequate for unstable ships. The linear estimation for fine forms, ballasted vessels, and all ships with relatively-large rudder sizes is satisfactory (Comstock, 1967; Della Loggia et al., 1977; Eda and Crane, 1965; Nomoto, 1960; Nomoto, 1966; Nomoto et al., 1957).

Results obtained for the seven full-form ships in the experiment are presented in Figures 2, 3, and 4. The best estimation was achieved for the 1000-foot Great Lakes carrier (Figure 2), which has a draft of only 27.5 ft and was modeled at Stevens Institute as a dynamically-stable ship (Eda et al., 1982). Comparison of the

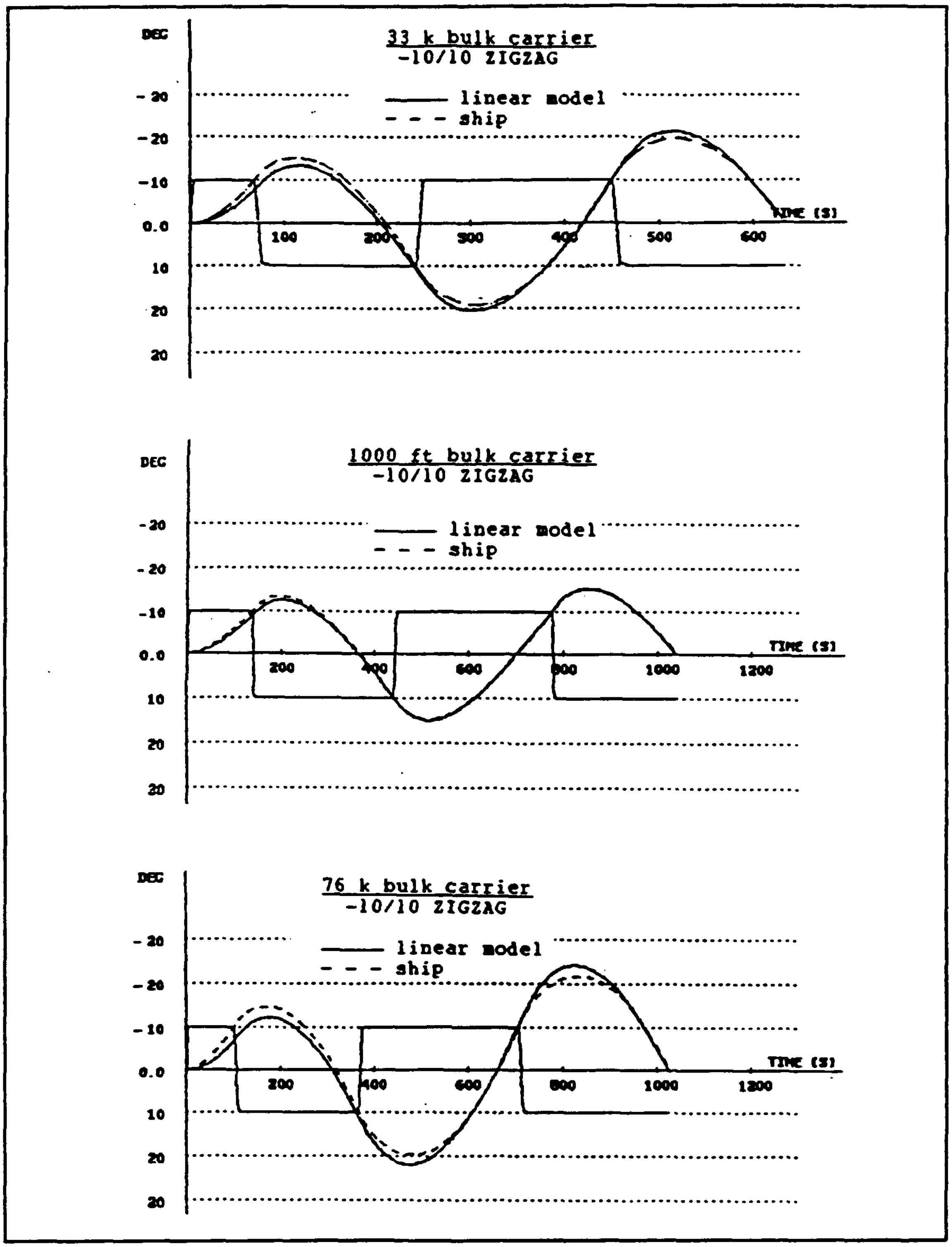

FIGURE 2. ZIGZAG MANEUVERS FOR THREE EXPERIMENTAL SHIPS, WITH THE NOMOTO MODEL'S APPROXIMATIONS

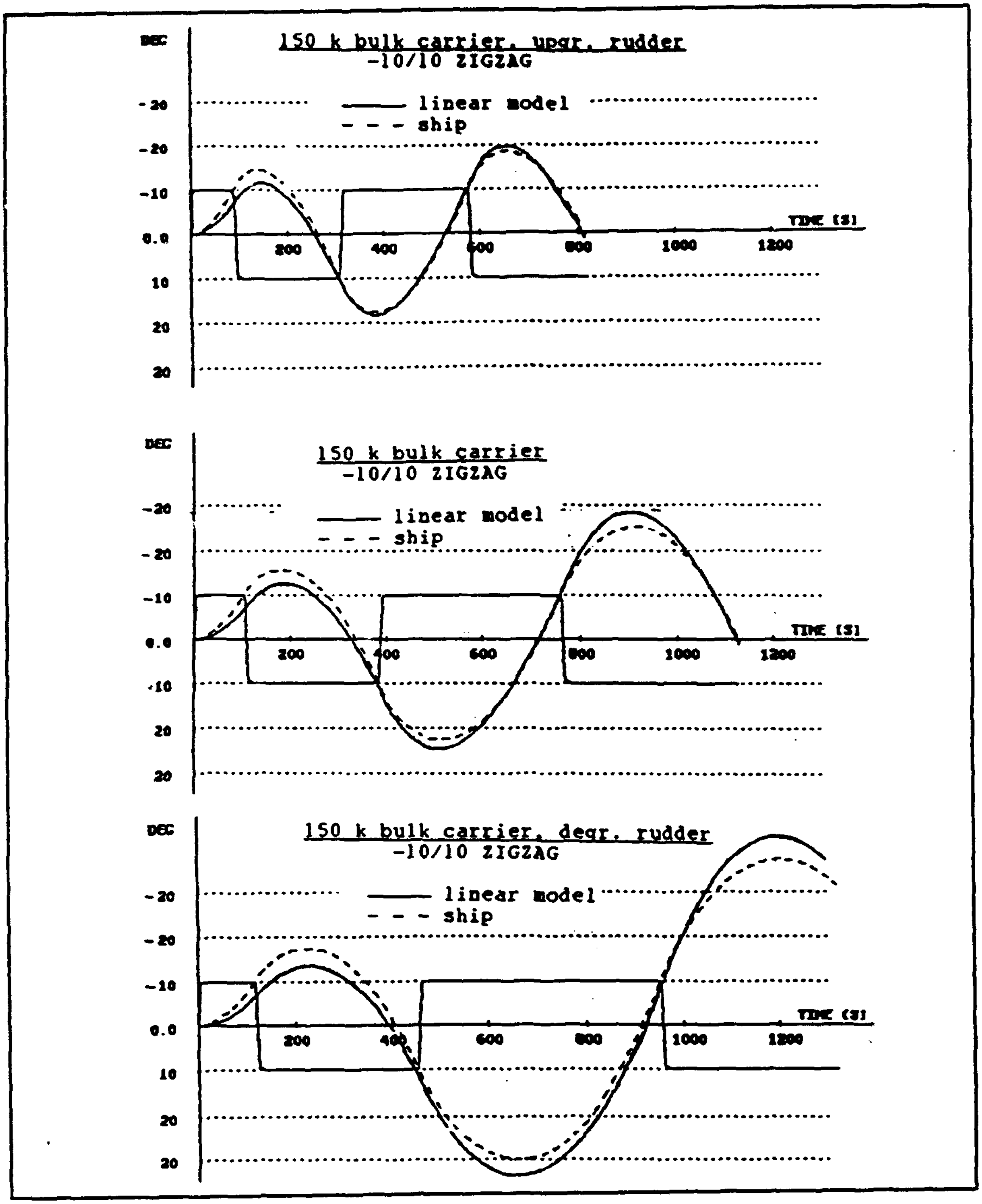

FIGURE 3. ZIGZAG MANEUVERS FOR THREE VERSIONS OF THE 150 K BULK CARRIER, WITH THE NOMOTO MODEL'S APPROXIMATIONS

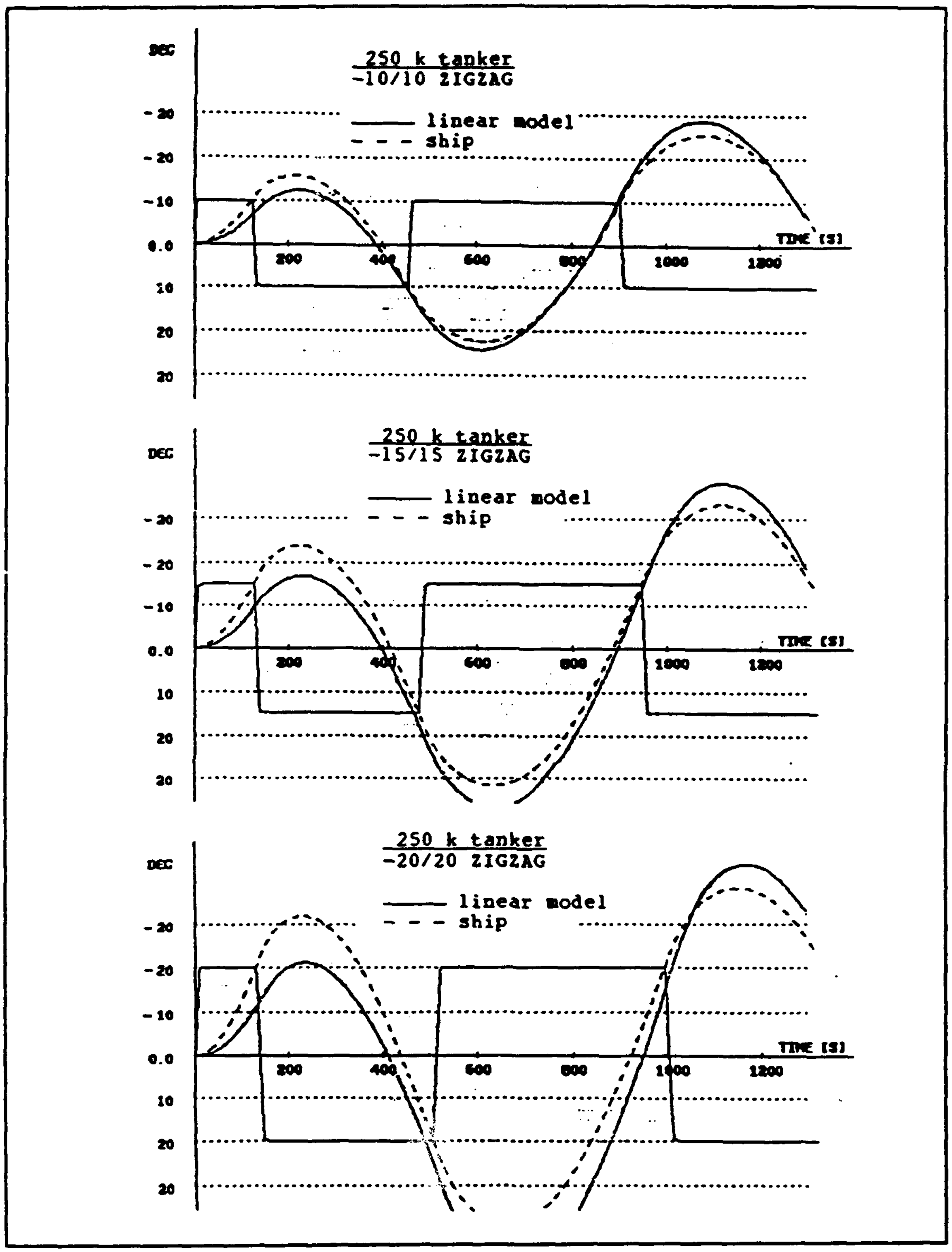

FIGURE 4. ZIGZAG MANEUVERS FOR THE 250 K TANKER, WITH THE NOMOTO MODEL'S APPROXIMATIONS

zigzag maneuvers of the 150 k bulk carrier equipped with three different rudders shows evident loss of adequacy of the linear model for the ship versions with smaller rudders (Figure 3).

The linear model is less adequate for maneuvers made with larger helm angles, as shown for the 250 k tanker in Figure 4. For the 10-degree zigzag, the estimation is fairly accurate, but it becomes respectively worse for 15-degree and 20-degree maneuvers. This trend appears because the nonlinearity of the ship has a greater contribution to the hydrodynamic forces in the 20-degree zigzag than at 10 degrees (Abkowitz, 1980). Speed loss, an important factor, must be ignored for simplified Model (5). Speed reduction is not small in the mild 10-degree maneuver, but becomes greater in tighter maneuvers. It is directly related to the ship's yaw and sway responses (Eda and Crane, 1965). These characteristics of the K and T coefficients are considered in the discussion of the relations developed in Section 4.

Nomoto also proposed an alternative measure of quickness of response to steering that can be obtained directly from the zigzag maneuver data. It is the "course lag time" defined as a time, T_L, elapsed from the instant when the rudder passes amidship to the instant when the ship reaches the extreme course deviation (Figure 1). A nondimensional equivalent of T_L is defined as follows:

$$T^*_L = T_L \cdot U/L \tag{8}$$

where: U denotes the ship speed, and L is the ship length between perpendiculars.

The expected strong correlation of T^* and T^*_L has been confirmed experimentally (Nomoto and Norrbin, 1969). As a result, the T^* value can be determined directly from the zigzag maneuver data.

N. H. Norrbin (SSPA) proposed the "course change quality number", P, as a measure of controllability. He defined that parameter using T and K Nomoto' indices as follows:

$$P = K^* (1 - T^* + e^{-1/T^*}) \tag{9}$$

He then reached a tentative conclusion that P > 0.3 may assure a reasonable standard for the course changing quality. Later, he extended this range to P > 0.2 for large tankers. Parameter P seems to be less dependent on the rudder angles than K and T. However, it should be used together with another index that represents stability on course for unstable ships. It can be T^* or T^*_L, as examples (Nomoto and Norrbin, 1969).

2.2 SELECTIONS FOR FURTHER ANALYSIS

For the analysis that follows, six indices were selected:

- **tactical diameter,**
- **overshoot angle,**
- **time to reach the first execute heading change,**
- **course lag time,**
- **K and T (Nomoto's indices),**
- **P (Norrbin's index).**

All dimensional and nondimensional values of the potential indices were considered. In addition, values of the potential indices associated with the zigzag maneuver were determined for -10/10, -15/15, and -20/20 zigzags. However, the -20/20 degrees maneuver was treated with special attention with respect to SNAME decisions. The course lag time was calculated according to Nomoto's recommendations, and also for the first overshoot only. The complete list of values of the potential indices for all ships involved in the experiment is presented in Appendix A.

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3.0 MEASUREMENT OF SHIP PILOTED PERFORMANCE

3.1 MEASURES OF PILOTED PERFORMANCE

The measurement of behavior as complex as pilot/ship/waterway performance requires some basic assumptions. The USCG Waterway Performance Project has followed recommendations on the use of simulators for port design published by the Society for Naval Architects and Marine Engineers (SNAME) and the Marine Board of the National Academy of Science (Panel H-10, SNAME, 1975; Atkins and Bertsche, 1980a and b). Generally, recommended measures of performance focus on the precision of ship tracks through the channel under stated conditions. In the Waterway Project, for expressing this precision, the primary performance measure has been the crosstrack distance from the channel's centerline of the ship's center of gravity at an alongtrack point in the transit. This measure lends itself to a variety of manipulations. A "track plot" can be constructed showing the crosstrack distance as a function of alongtrack distance in the transit. The crosstrack distribution of a set of track plots at a selected alongtrack distance can be described by its mean (MN) and standard deviation (SD). The MN and SD of the distribution of tracks can be considered separately as measures of precision. Together, they can be used to calculate the probability that the tails of the Gaussian distribution that describes the observed tracks will exceed the channel edges and that there will be a "grounding."

Earlier work in the Waterway project has used the Relative Risk Factor (RRF) to quantify the probability of grounding. The derivation of this measure is described elsewhere (Bertsche, Smith, Cooper, and Marino. 1982; Smith, Marino, and Multer, 1985). The general concept of the RRF is illustrated in Figure 5. The MN crosstrack position of the ship's center of gravity at a specific point in the transit is adjusted (for the beam and the mean heading relative to the channel) to represent the distributions of the extreme points of the ship's contour most exposed to the channel edge. A Gaussian distribution, with the SD observed for multiple transits by multiple pilots, is assumed around each of the extreme MNs and the probabilities of grounding to port (P_p) and to starboard (P_s) are calculated. The total probability of grounding on either channel edge is the RRF for that region of the channel.

Because the calculation of the RRF for a given set of conditions requires the MN and the SD for that set of conditions, these two statistics were used as the primary measures of piloted performance for the present analysis. The MN of the ship's center of gravity was used as the most general indication of the ship's position. The MN position of any of the ship's extreme points can be calculated for any beam and relative heading. This approach

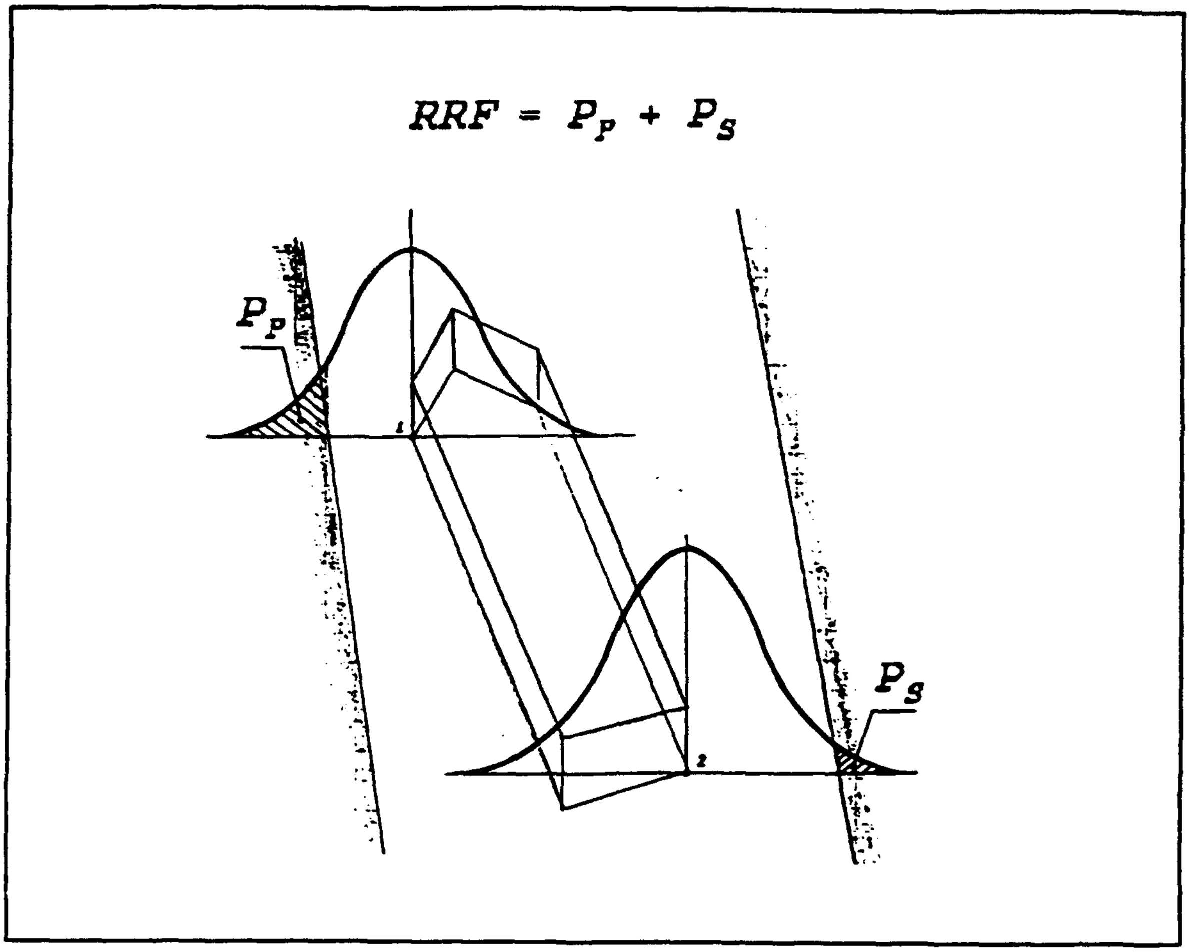


FIGURE 5. THE GENERAL CONCEPT OF THE RELATIVE RISK FACTOR (RRF)

requires a few minor simplifications at the level of the ship heading statistics, but the use of the ship's center of gravity as the basis of a prediction methodology is commonly accepted in ship hydrodynamics.

The need for nondimensional forms for MN and SD must be anticipated in the case of relations involving nondimensional independent variables. Nondimensional coefficients have been used in all branches of ship theory. The chosen unit for distance is almost always the length of the concerned body. For the common surface ship, it is the length between perpendiculars (Comstock, 1967; Davidson and Schiff, 1946; Gertler and Gover, 1960; Newman, 1977; and Norrbin, 1969) It seems reasonable to extend that approach to the MN and SD. Thus, the MN and SD were nondimensionalized by dividing by the length of the vessel. These nondimensional forms were used for the transform for channel width discussed in Section 3.3 and for the turn region's regression model

discussed in Section 4.2. In the final equations, summarized in Section 4.5, these statistics are expressed in their dimensional forms.

3.2 PILOTED PERFORMANCE FOR THE MANEUVERING REGIONS

3.2.1 Overview of the Approach

The selection of the data to be used in the development of the regression models required some organizing assumptions, which are briefly described below:

1. Independent selection for each maneuvering region. The difference in demands made on the ship's inherent maneuverability by the several constituent maneuvers of a waterway transit implies that piloted performance may be dependent on different indices of ship inherent controllability in each maneuvering region. (The maneuvering requirements for the experimental transit are reviewed briefly in Section 1.4 in the present report. They are also discussed in some greater detail in the separate report on the experiment, Smith et al., 1990.) With this expectation, data were selected independently in each region. After an initial review of the data, two groups of regions were established. Group A comprises the regions with significant activity of the rudder and meaningful risk in the pilot's perception: the turn, the turn-recovery, the recovery, and the entry regions. Group B comprises the regions with negligible activity of the rudder and low risk in the pilot's perception: the trackkeeping and the turn-entry regions. The nature of the maneuver in each region is described below. The two groups of regions are treated differently in the transformation for channel width described in Section 3.3 that follows and in Section 4 where the development of the regression models is described. Regression models based on inherent controllability indices were developed only for the waterway regions belonging to the Group A. Models for Group B were based on a single physical dimension.

2. Homogeneous piloting techniques. Calculation of the RRF based on a Gaussian distribution requires homogeneous pilot techniques which can be expected to produce a distribution of tracks with a mean of zero and a random variability. Homogeneity is especially important for this analysis where variations in pilot technique or intention could blunt the response of the observed ship's track to ship inherent controllability. Homogeneity was achieved in this analysis by examining the recorded data for each transit for patterns common to the ship and to the region. To be included in the analysis for a region, a specific transit had to meet two criteria. First, it had to exhibit a pattern of crosstrack position, crab angle (heading relative to the channel course), and rudder angle similar to the majority of other transits through that region. Second, the maximal crosstrack distance from the center-

line achieved in that region could not be affected in an obvious way by the familiarization of the pilot with the simulator, the experimental channel, or the ship. (The piloting techniques for each region are described in greater detail in the experimental report, Smith et al., 1990.)

3. Position of the ship's center of gravity as the primary measure. The crosstrack position of the ship's center of gravity was used as the primary measure of piloted performance. Because the risk of grounding is in the exposure of the ship's extreme points to the boundaries of the channel, as illustrated in Figure 5, each transit was examined for the closest approach of the extreme points to boundary and the crosstrack position of the ship's center of gravity was selected at that alongtrack position.

As an overview of the selection and preparation of the piloted performance data, each individual transit was examined by maneuvering region for a pattern characteristic of that region. Transits that demonstrated a characteristic pattern were represented by the crosstrack position of the ship's center of gravity at the point of maximal exposure of an extreme point to the channel edge. A small minority of transits were eliminated from the analysis in a given region to ensure homogeneity of technique. The MNs and SDs were calculated for each ship and each region. Each of the seven ships evaluated could be represented in each region by a maximum of 16 transits. This selection of the data and the resulting values are the subject of this section.

3.2.2 Selection of Data in the Turn Region

A sample of the characteristic maneuver in the turn region is illustrated in Figure 6. The figure shows successive contours of the ship against the outline of the channel in the immediate region of the turn. Each contour is positioned with the ship's center of gravity on a "dataline," an imaginary line spaced at intervals along the channel. The darkened contour is of interest. Vertices 1 and 3 are the points of the ship's simplified contour most exposed to grounding. The closest position of the ship's contour to the channel's outline was determined when Point 1 was projected on Dataline 0. At that moment, the ship's center of gravity was recorded on Dataline -1. The crosstrack position of the center of gravity at Dataline -1 was included in the calculation of the MN and SD for the subject ship for the turn region. A similar examination was performed for each of the 112 transits. Piloting techniques in this region appeared homogeneous and only one transit was rejected for a total of 111 transits included in further analyses.

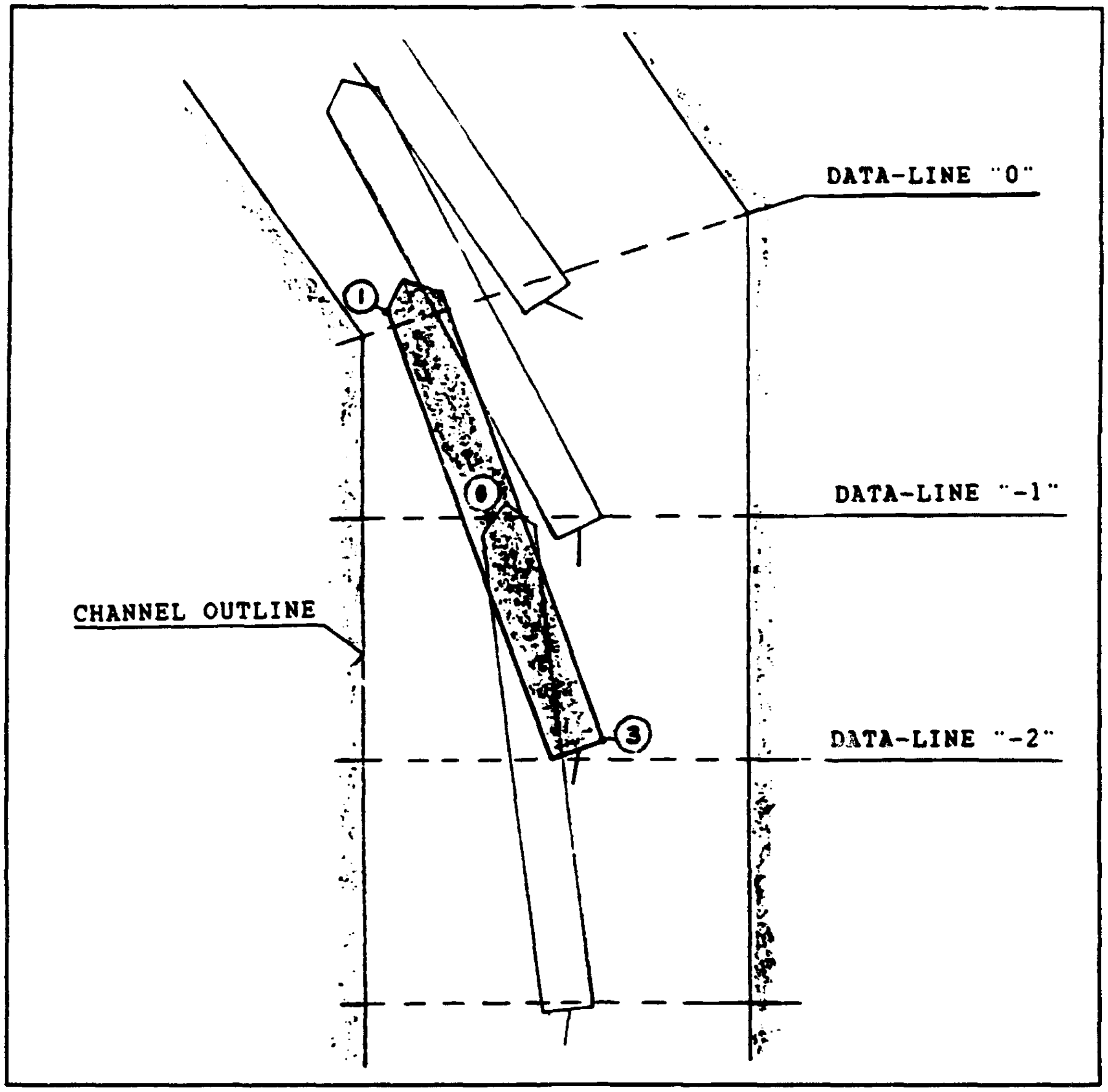


FIGURE 6. SHIP'S EXPOSURE TO GROUNDING IN THE TURN REGION

Turn region data are presented in Table 4 for all seven ships. Shown in the first block are the MNs and SDs for the maximal crosstrack positions of the two most exposed vertices of the ship contour. Positive values of the MN are to the right of the channel centerline; minus values are to the left. In the second block are the values for the center of gravity of the ship. The "T" values are transformed to comparable channel widths by a procedure discussed in Section 3.3, which follows.

TABLE 4. BASIC STATISTICS FOR THE TURN REGION

	SHIP	MN 1 [ft]	SD 1 [ft]	MN 3 [ft]	SD 3 [ft]
1	33 k	-101	47	133	51
2	1000 ft	-177	73	217	80
3	76 k	-154	72	206	89
4	150 k (r)	-205	49	180	69
5	150 k (d)	-191	58	190	87
6	150 k (u)	-221	35	168	57
7	250 k	-261	66	219	95

Continuation.

	SHIP	MNo [ft]	MNo T [ft]	SDo [ft]	SDo T [ft]
1	33 k	10	8	47	49
2	1000 ft	12	-10	72	91
3	76 k	18	5	75	86
4	150 k (r)	-23	-23	53	53
5	150 k (d)	-11	-11	65	65
6	150 k (u)	-38	-38	35	35
7	250 k	-35	-36	75	76

MN 1, SD 1, and MN 3, SD 3 are the Mean and Standard Deviation values for the maximal cross-track positions of the Vertices 1 and 3 respectively.

MNo and SDo are the Mean and Standard Deviation values for the cross-track position of the ship's center of gravity.

MNo T and SDo T are MNo and SDo transformed to the same relative width of the channel.

3.2.3 Selection of Data in the Turn-recovery Region

Establishment of the shiphandling technique was the most difficult in the turn-recovery region. Both the ship movement caused by the turn and the impact of the water current (broad from the port quarter in this region) contributed to the ship's sway movement to the outside edge of the channel. To counter that movement, a few degrees of crab angle had to be maintained when the ship was just near the channel edge. There was some variation among pilots and transits as to just how this relatively-more-difficult maneuver was performed. As illustrated in Figure 7, the

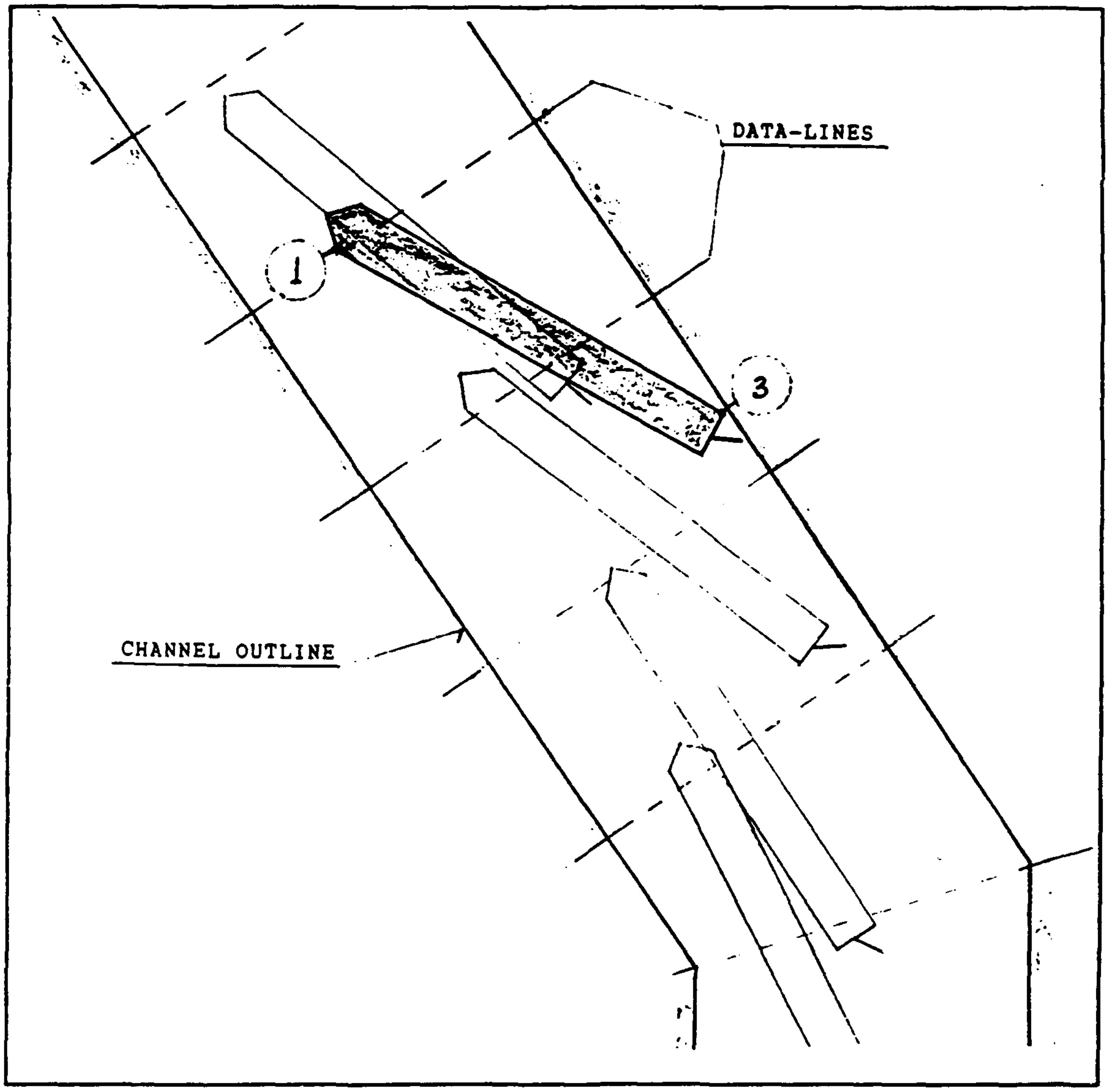


FIGURE 7. SHIP'S EXPOSURE IN THE TURN-RECOVERY REGION

Vertex 3 of the ship contour was most exposed to the grounding. The Vertex 1 was selected as a second point for the analysis. Its exposure to grounding could be more substantial in the absence of the crosscurrent. Maximal deviations of the Vertices 1 and 3 were determined at the same point of the ship's track. However that point was differently located along the channel in different transits. In each transit, position of the ship's center of gravity associated with the maximal deviation of the Vertices 1 and 2 was used in the analysis. Less agreement in intended track and rudder use resulted in the acceptance of fewer transits. Here, 101 transits were included in further analyses. The resulting calculated values for this region are presented in Table 5.

TABLE 5. BASIC STATISTICS FOR THE TURN-RECOVERY REGION

	SHIP	MN 1 [ft]	SD 1 [ft]	MN 3 [ft]	SD 3 [ft]
1	33 k	-13	45	111	46
2	1000 ft	3	68	187	70
3	76 k	5	60	184	61
4	150 k (r)	5	75	261	78
5	150 k (d)	32	91	298	93
6	150 k (u)	16	67	222	70
7	250 k	37	93	324	95
Continuation.					
	SHIP	MNo [ft]	MNo T [ft]	SDo [ft]	SDo T [ft]
1	33 k	47	50	45	45
2	1000 ft	93	127	67	76
3	76 k	92	109	59	63
4	150 k (r)	128	128	74	74
5	150 k (d)	159	159	88	88
6	150 k (u)	116	116	65	65
7	250 k	175	176	92	92

MN 1, SD 1, and MN 3, SD 3 are the Mean and Standard Deviation values for the maximal cross-track position of the Vertices 1 and 3 respectively.

MNo and SDo are the Mean and Standard Deviation values for the cross-track position of the ship's center of gravity.

MNo T and SDo T are MNo and SDo transformed to the same relative width of the channel.

3.2.4 Selection of Data in the Recovery Region

Two different techniques were used by the pilots at the exit of the turn-recovery region. In a few cases, the ship was handled to reach the channel centerline asymptotically, a technique that requires an unlimited distance along the channel. In the majority of cases, the ship was handled to reach the centerline in a more resolute manner. This last technique was selected because it included the far-larger number of cases and, being more difficult, was likely to be more strongly dependent on ship inherent controllability. The maneuver is illustrated in Figure 8.

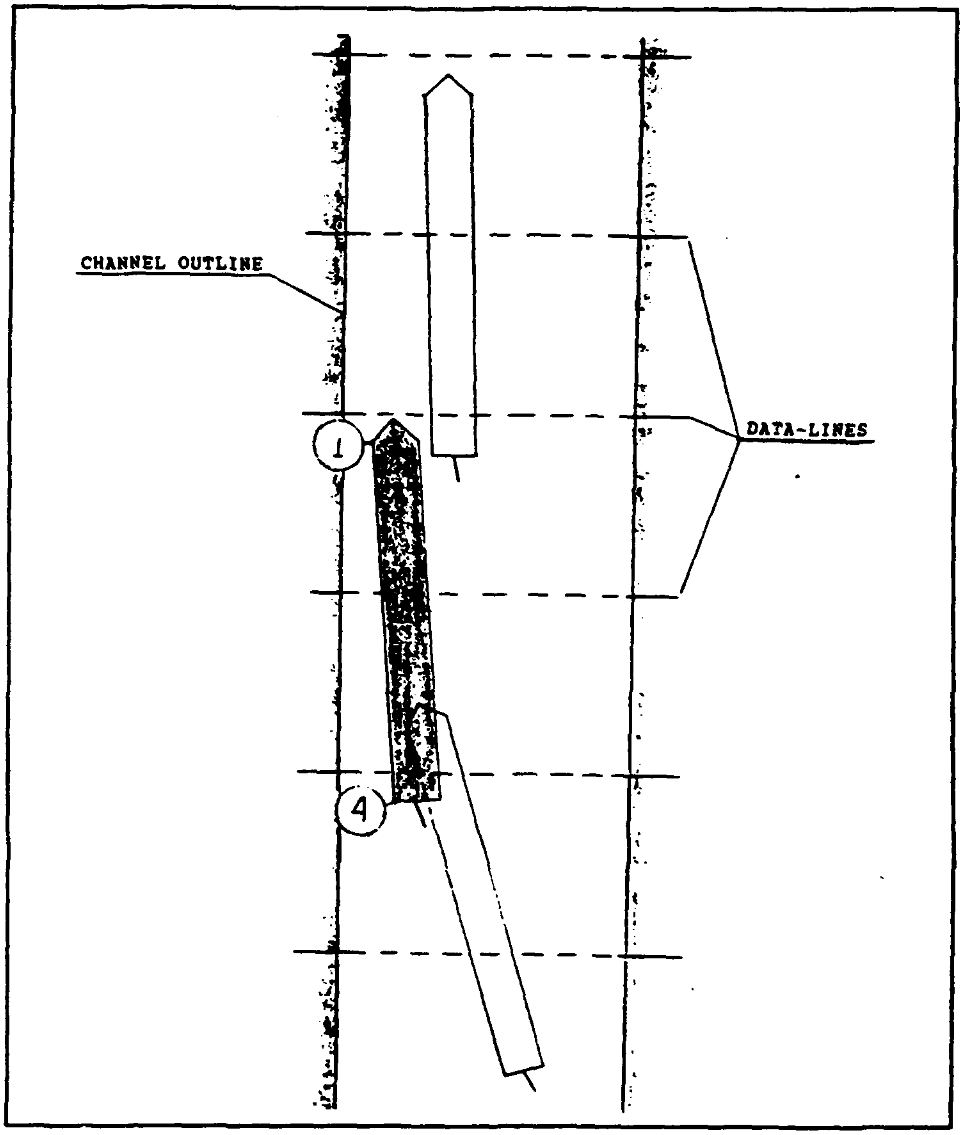


FIGURE 8. EXPOSURE IN THE RECOVERY AND ENTRY REGIONS

Vertex 1 was determined to be the point of the ship's simplified contour most exposed to grounding in the recovery region. Vertex 4 has been selected as a second point for consideration. The maximal deviation of the ship's contour was differently located along the channel in different transits. In each transit, position of the ship's center of gravity associated with the maximal deviation of Vertex 1 was used in the analysis. Limiting the selected transits to only the more-frequent technique resulted in the inclusion of 89 homogeneous transits of the 112 possible transits. The resulting data are presented in Table 6.

3.2.5 Selection of Data in the Entry Region

The techniques used by the pilots entering the channel were similar to the techniques executed in the recovery region. The ship was handled, either to reach the channel centerline asymptotically, or to get to the centerline in a more resolute manner. As was the case for the recovery region, only transits employing the second techniques were considered. It included the greater number of cases and was expected to be more dependent on ship inherent controllability. Because of the similarity of the maneuver in the entry region to that in the recovery region, a separate figure is not presented. Again, because only the dominant of two techniques was used, a relatively-small number of transits were included. This region was represented by 88 out of a potential 112 transits. The obtained values are presented in Table 7. (No transformation for channel width was done in this region. Its influence was minor in the entry region and no meaningful pattern was determined. Consequently, the original data were used in the analysis.)

TABLE 6. BASIC STATISTICS FOR THE RECOVERY REGION

	SHIP	MN 1 [ft]	SD 1 [ft]	MN 4 [ft]	SD 4 [ft]
1	33 k	-54	24	-42	28
2	1000 ft	-83	38	-51	44
3	76 k	-80	43	-59	45
4	150 k (r)	-104	46	-86	55
5	150 k (d)	-130	68	-114	71
6	150 k (u)	-93	37	-81	40
7	250 k	-120	56	-103	60

Continuation.

	SHIP	MNo [ft]	MNo T [ft]	SDo [ft]	SDo T [ft]
1	33 k	-6	-6	26	24
2	1000 ft	-16	-10	41	24
3	76 k	-18	-15	44	36
4	150 k (r)	-23	-23	50	50
5	150 k (d)	-50	-50	69	69
6	150 k (u)	-15	-15	38	38
7	250 k	-27	-27	58	57

MN 1, SD 1, and MN 4, SD 4 are the Mean and Standard Deviation values for the maximal cross-track position of the Vertices 1 and 4 respectively.

MNo and SDo are the Mean and Standard Deviation values for the cross-track position of the ship's center of gravity.

MNo T and SDo T are MNo and SDo transformed to the same relative width of the channel.

TABLE 7. BASIC STATISTICS FOR THE ENTRY REGION

	SHIP	MN 1 [ft]	SD 1 [ft]	MN 4 [ft]	SD 4 [ft]
1	33 k	-63	22	-69	41
2	1000 ft				
3	76 k	-90	15	-102	16
4	150 k (r)	-126	31	-136	33
5	150 k (d)	-140	30	-156	39
6	150 k (u)	-130	23	-138	28
7	250 k	-124	33	-142	36

Continuation.

	SHIP	MNo [ft]	MNo T [ft]	SDo [ft]	SDo T [ft]
1	33 k	-24		23	
2	1000 ft	-36		26	
3	76 k	-43		15	
4	150 k (r)	-58		32	
5	150 k (d)	-75		34	
6	150 k (u)	-61		25	
7	250 k	-47		34	

MN 1, SD 1, and MN 4, SD 4 are the Mean and Standard Deviation values for the maximal cross-track position of the Vertices 1 and 4 respectively.

MNo and SDo are the Mean and Standard Deviation values for the cross-track position of the ship's center of gravity.

MNo T and SDo T are MNo and SDo transformed to the same relative width of the channel.

3.2.6 Selection of Data in the Turn-entry Region

The turn-entry region includes the initial changes of the ship's crosstrack position made by a pilot before execution of the turn maneuver in an effort to minimize the risk in the turn. Thus, the ship's position is mainly associated with size of the ship and the exposure to grounding in the turn-entry region is relatively small. However, a significant crosstrack distance can affect the risk of grounding. The maneuver is illustrated in Figure 9.

Vertices 2 and 3 have been determined to be the points of the

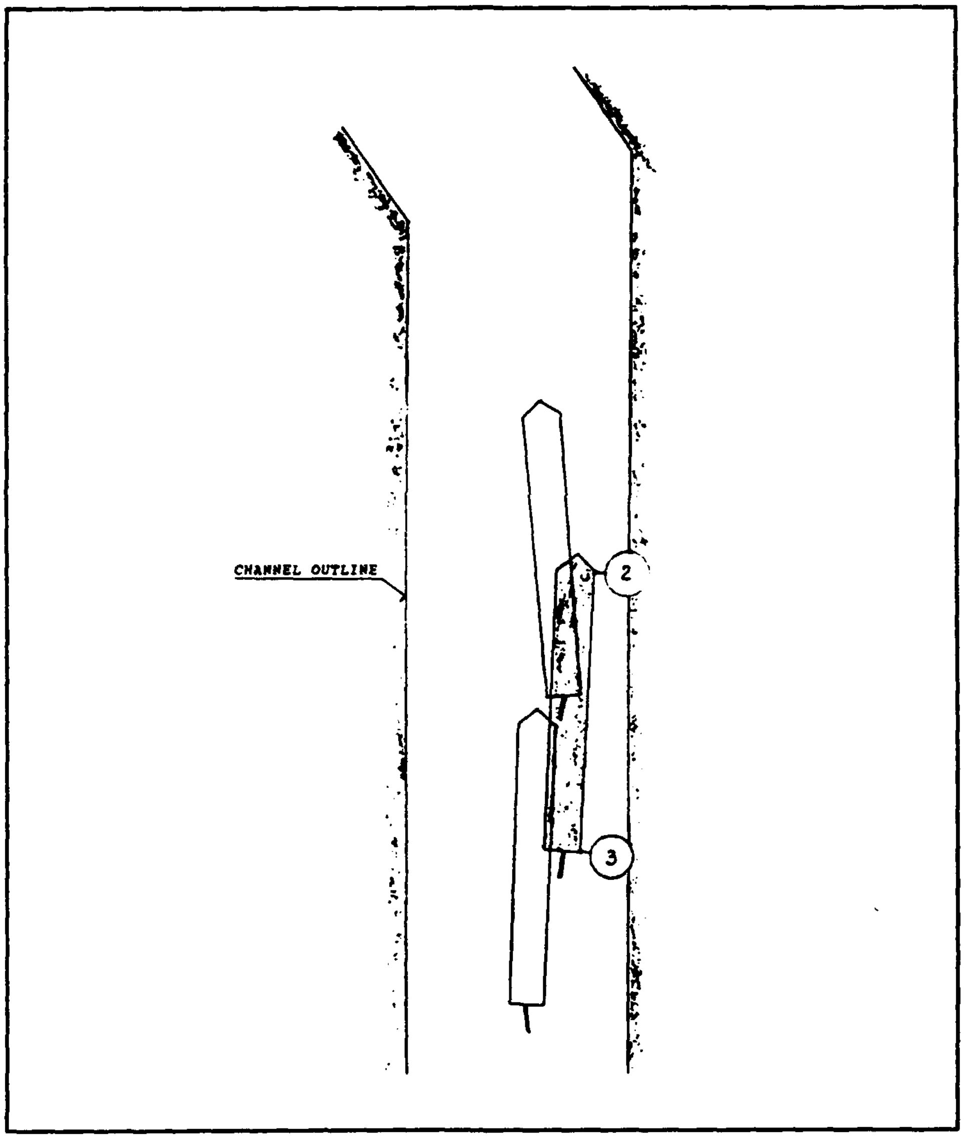


FIGURE 9. SHIP'S EXPOSURE TO GROUNDING IN THE TURN-ENTRY REGION

ship's simplified contour that were most exposed to grounding in the turn-entry region. Maximal deviation of the ship's contour was differently located along the channel in different transits. In each transit, position of the ship's center of gravity associated with the maximal deviation of the Vertex 2 was selected. All transits were included in the calculations. Basic statistics for the turn-entry region are listed in Table 8. (No meaningful pattern was determined for influence of the channel width. Consequently, the original data have been used in the calculations.)

TABLE 8. BASIC STATISTICS FOR THE TURN-ENTRY REGION

	SHIP	MN 2 [ft]	SD 2 [ft]	MN 3 [ft]	SD 3 [ft]	MN 0 [ft]	SD 0 [ft]
1	33 k	120	46	110	42	73	44
2	1000 ft	150	62	130	50	88	56
3	76 k	144	78	126	66	82	72
4	150 k (r)	115	43	103	35	37	38
5	150 k (d)	116	49	101	39	37	44
6	150 k (u)	101	34	92	32	24	32
7	250 k	131	55	110	43	37	49

MN 2, SD 2, and MN 3, SD 3 are the Mean and Standard Deviation values for the maximal cross-track position of the Vertices 2 and 3 respectively.

MNo and SDo are the Mean and Standard Deviation values for the cross-track position of the ship's center of gravity.

3.2.7 Selection of Data in the Trackkeeping Regions

There were trackkeeping regions in both legs of the experimental channel. Different directions of the water current and the wind made a practical distinction between these regions. The data selection was conducted for both regions independently. However, the finally-selected forms of the regression models will be the same.

The trackkeeping region includes a part of the ship's transit where the rudder is fixed and the ship is assumed to maintain the course parallel to the channel edge. According to that assumption, some transits had to be excluded from the sample. Calculations were made on 104 transits in Leg 1 and 95 transits in Leg 2.

Vertices 1 and 3 were determined to be the points of the ship's simplified contour most exposed to grounding in the trackkeeping regions. The regions were differently located along the channel in different transits. In each transit, position of the ship's center of gravity associated with the maximal deviation of the Vertex 1 was used in the risk calculations.

Basic statistics of the trackkeeping regions are listed in Table 9. (Influence of the channel width was minor in the regions. Consequently, the original data were used.)

TABLE 9. BASIC STATISTICS FOR THE TRACKKEEPING REGIONS

CHANNEL LEG 1

	SHIP	MN 1 [ft]	SD 1 [ft]	MN 3 [ft]	SD 3 [ft]	MN 0 [ft]	SD 0 [ft]
1	33 k	-38	24	26	42	4	25
2	1000 ft	-50	34	34	50	1	34
3	76 k	-68	21	23	66	-16	22
4	150 k (r)	-71	43	44	35	1	43
5	150 k (d)	-83	43	43	39	-11	43
6	150 k (u)	-70	44	45	32	3	45
7	250 k	-90	44	44	43	- 4	44

CHANNEL LEG 2

	SHIP	MN 1 [ft]	SD 1 [ft]	MN 3 [ft]	SD 3 [ft]	MN 0 [ft]	SD 0 [ft]
1	33 k	-40	27	56	29	7	28
2	1000 ft	-40	37	93	43	26	39
3	76 k	-68	30	65	40	-2	34
4	150 k (r)	-53	46	110	53	28	49
5	150 k (d)	-51	46	110	43	29	44
6	150 k (u)	-52	36	112	43	29	39
7	250 k	-51	34	138	42	42	37

MN 1, SD 1, and MN 3, SD 3 are the Mean and Standard Deviation values for the maximal cross-track position of the Vertices 1 and 3 respectively.

MNo and SDo are the Mean and Standard Deviation values for the cross-track position of the ship's center of gravity.

3.3 CHANNEL WIDTH AND SHIP SIZE

The relations "MN versus Inherent Controllability" and "SD versus Inherent Controllability" can be determined using experimental data if all factors other then Inherent Controllability remain constant for all ships. In the case of data from the simulator experiment, the only consideration is the impact of the channel width relative to the ship size. The requirement for constancy introduces a number of questions. For instance, which channel widths are relatively the same for the 250,000 dwt (250 k) tanker and the 1000-foot bulk carrier? Is the relative width valid for the whole channel, or does its definition change from one waterway maneuvering region to another? The determination of definite answers to these, and other related questions, requires separate research and considerable data. To allow the present analysis, a few reasonable hypotheses were developed by the logic described below.

As an early step in the treatment of the data, two alternative definitions of "relative width of channel" were examined that would allow the transformation of the performance MNs and SDs for all ships to the same relative channel width before they were to be used together in a regression formula:

- Definition A: the channel width relative to the ship size is the ratio of the channel width to the ship <u>length</u>:

$$W_c^* = W_c/L \tag{10}$$

- Definition B: the channel width relative to the ship size is the ratio of the ratio of the channel width to the ship <u>beam</u>:

$$W_c^* = W_c/B \tag{11}$$

The ship and experimental channel dimensions and the relative channel widths according to both definitions are presented in Table 10. The relative channel widths for all ships are illustrated Figures 10 and 11. The relative width of the channel used for three versions of 150 k bulk carrier was selected as a baseline for all ships used in the comparative analysis of ship piloted performance. In Figures 10 and 11, this baseline is the vertical line through Points 6, 7, and 8. For Definition A this value is 0.872; while for Definition B, it is 5.503. Because the 150 k bulk carrier represents 3 of the 7 ships to be included in the analysis, this baseline means that minimal transformations of the MNs and SDs are necessary.

The consequences of the Definitions A and B are different, as illustrated in Figures 10 and 11. As examples, the 33 k bulker,

TABLE 10. SHIP LENGTH, BEAM, AND CHANNEL WIDTH IN THE EXPERIMENT

SHIP		LENGTH	BEAM	W C	W C /L	W C /B
1	33 k	574	85.3	489	.852	5.733
2	1000ft	990	105.0	757	.765	7.210
3	76 k	855	105.8	685	.801	6.474
4	76 k	855	105.8	543	.635	5.132
5	76 k	855	105.8	400	.468	3.781
6	150 k/r	915	145.0	798	.872	5.503
7	150 k/d	915	145.0	798	.872	5.503
8	150 k/u	915	145.0	798	.872	5.503
9	250 k	1085	170.0	943	.869	5.547

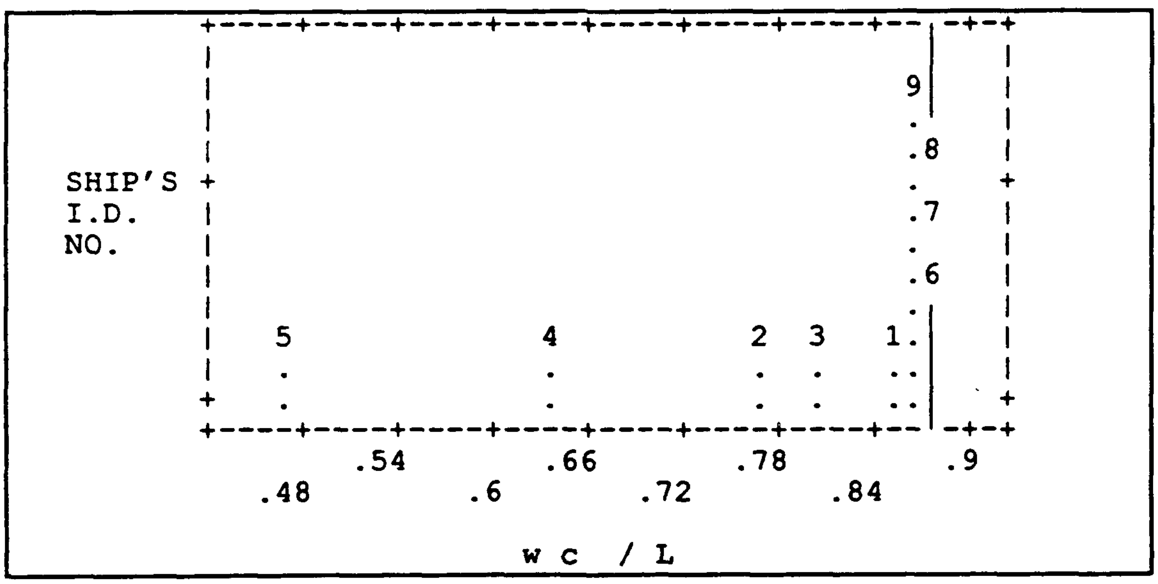


FIGURE 10. CHANNEL WIDTH TO SHIP LENGTH RATIOS IN THE EXPERIMENT

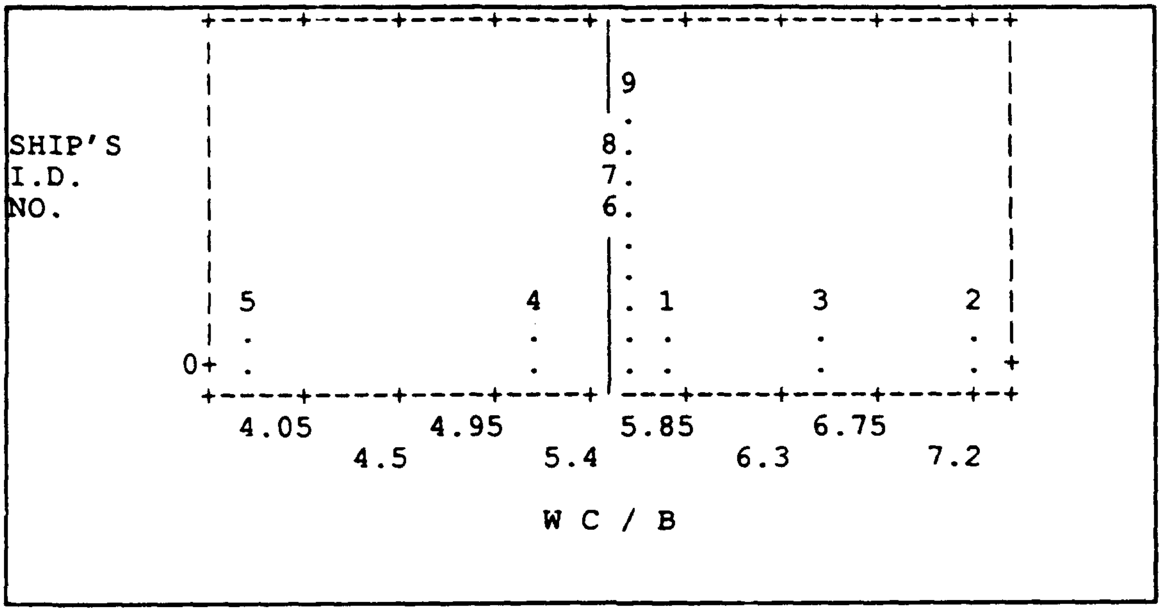


FIGURE 11. CHANNEL WIDTH TO SHIP BEAM RATIOS IN THE EXPERIMENT

the 1000-ft bulker, and the 76 k bulker were run with a smaller ratio of channel width to ship length than was the baseline 150 k bulk carrier. (See Table 10.) According to the Definition A (length), the MNs and SDs for them must be transformed to wider channels to achieve the same relative width (ratio) as that of the 150 k bulker. (See Figure 10, Points 1, 2, and 3). Conversely, these three ships were run with a larger ratio of channel width to ship beam than was the baseline 150 k bulker and, according to the Definition B (beam), their MNs and SDs must be transformed to narrower channels to achieve the relative width of the baseline 150 k tanker. (See Figure 11, Points 1, 2, and 3.) The required transformations were accomplished using the formulas described below.

Formulas describing the dependency of MN and SD on the channel width were developed using data collected in transits of the 76 k bulk carrier through three channel configurations, differing only in width. The dependency is illustrated in Figures 12, 13, 14, and 15. Data are presented for the three most difficult maneuvering regions in the transit: the turn, turn-recovery, and recovery. The division of the transits into "regions" is described in the immediately preceding Section 3.2. Note that in Figures 12, 13, 14, and 15 "MN_0" refers to the ship's center of gravity, the zero point for further calculations also discussed in Section 3.2. The symbol "-" is a convention to indicate that a variable has no dimension. The nondimensional forms are first introduced in Section 3.1

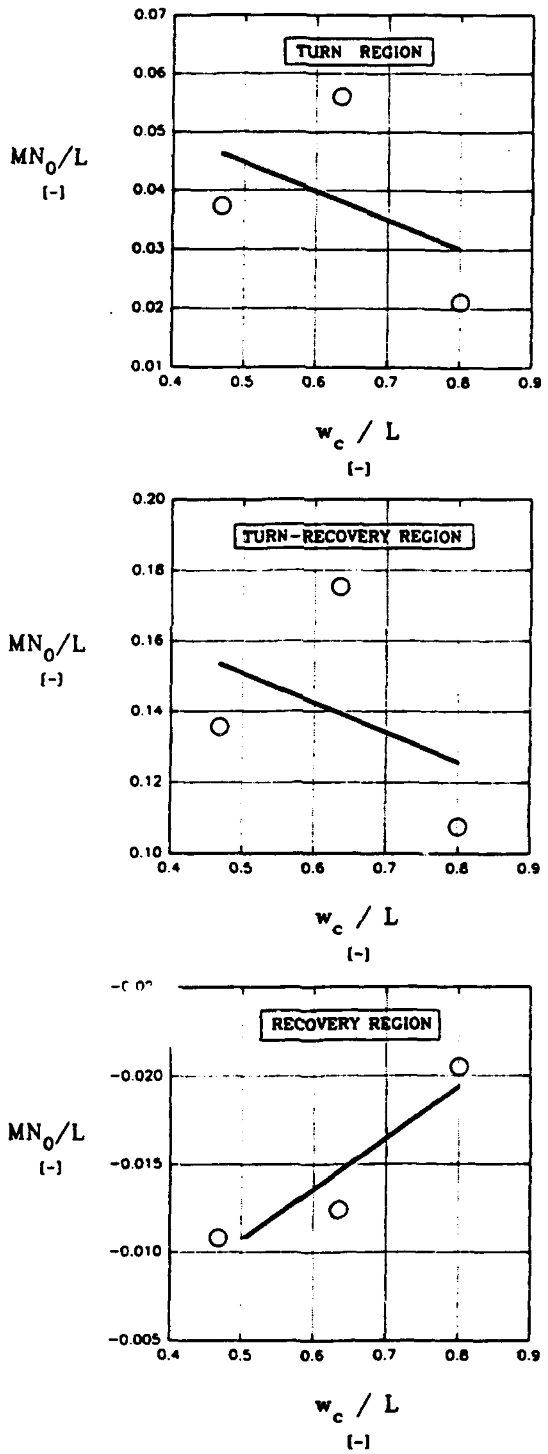


FIGURE 12. MN VERSUS CHANNEL WIDTH (BOTH OVER SHIP LENGTH)

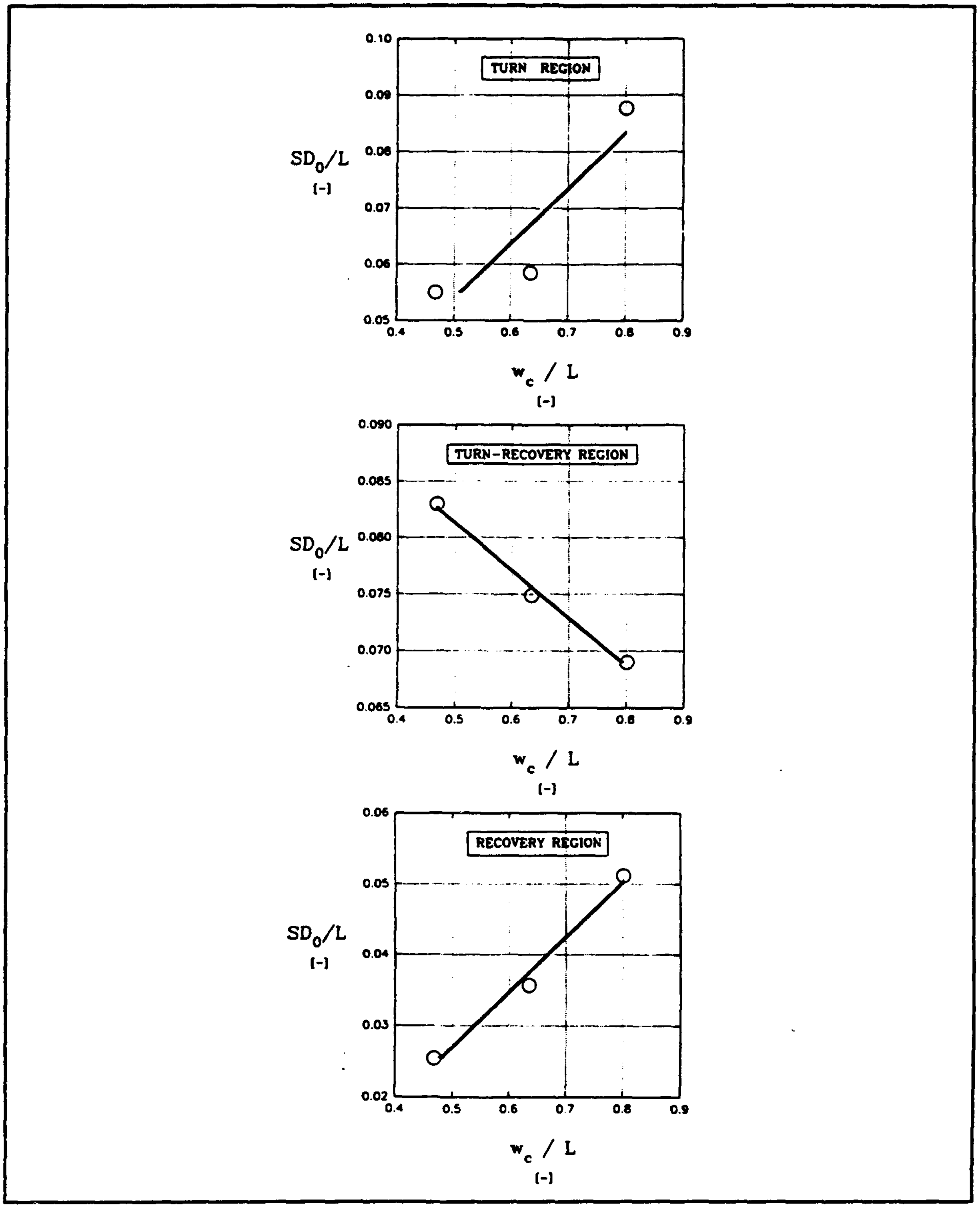


FIGURE 13. SD VERSUS CHANNEL WIDTH (BOTH OVER SHIP LENGTH)

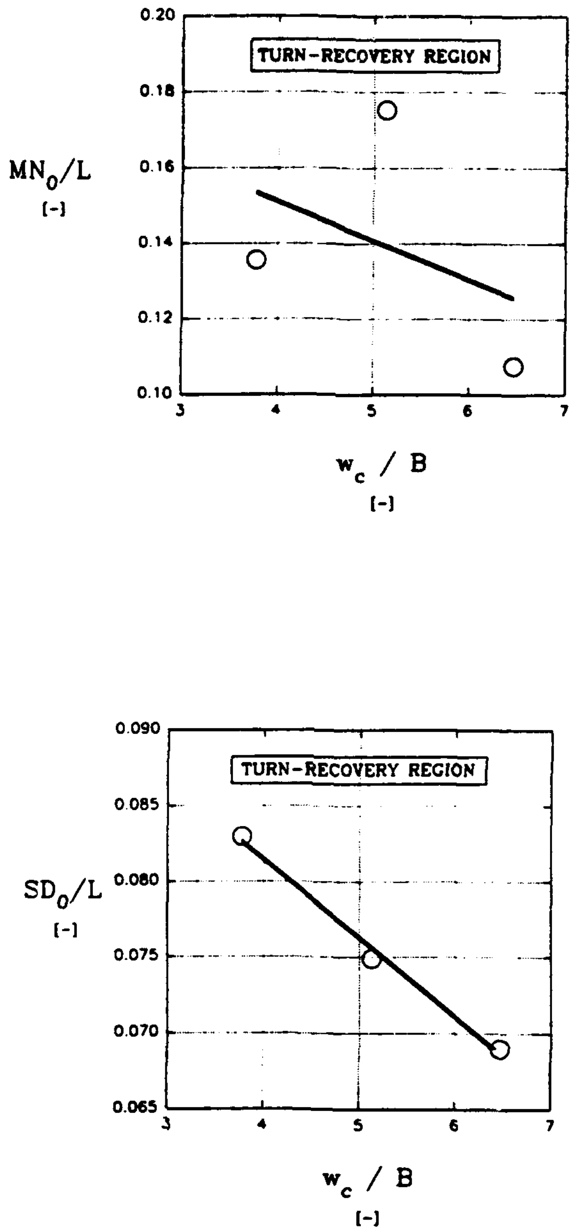


FIGURE 14. MN AND SD (OVER LENGTH) VERSUS CHANNEL WIDTH (OVER BEAM) IN TURN-RECOVERY REGION

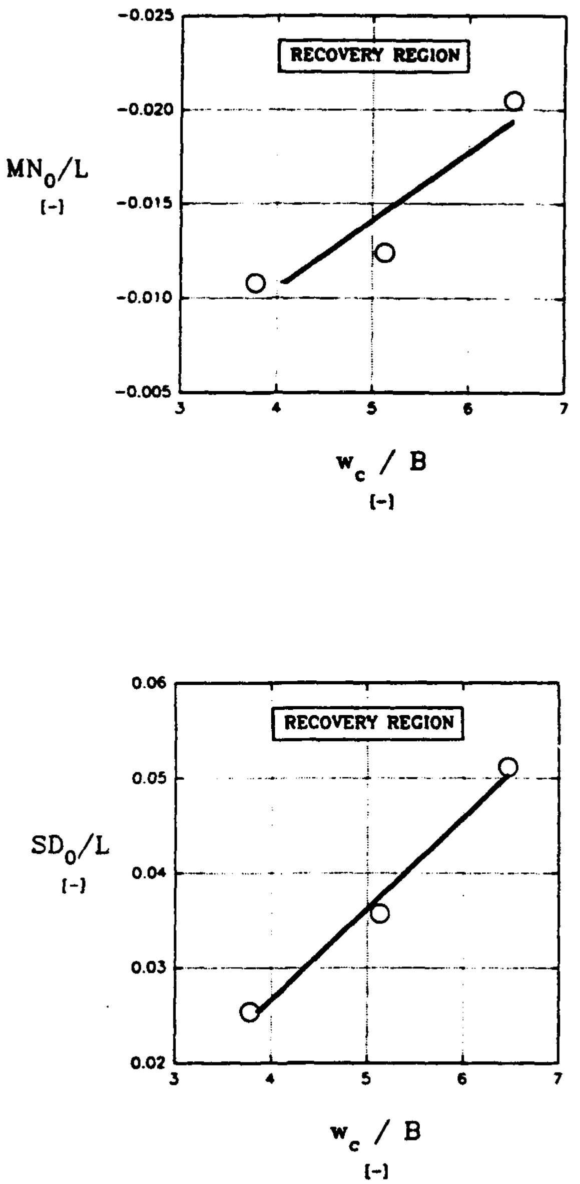


FIGURE 15. MN AND SD (OVER LENGTH) VERSUS CHANNEL WIDTH (OVER BEAM) IN RECOVERY REGION

The data determine three points on the "MN (or SD) - relative width" plane. Thus, only the straight line estimation is reasonable. Application of such a formula based on the one ship's data to other ships is possible with the additional assumption that the slope of the straight line is the same for all ships. It leads to the following formulas:

$$MN^* = (MN^*)_1 + SLOPE_{MN}^{76} \times [\, W_C^* - (W_C^*)_1 \,] \tag{12}$$

$$SD^* = (SD^*)_1 + SLOPE_{SD}^{76} \times [\, W_C^* - (W_C^*)_1 \,] \tag{13}$$

where: MN^* is a relative MN transformed to the same relative channel width as the baseline 150 k bulker, $(MN^*)_1$ is the nondimensional MN or MN/L observed for a subject ship, $SLOPE_{MN}^{76}$ is the slope calculated for the MNs of the 76 k tanker in the three widths of channel (as in Figures 12, 13, 14, and 15 and in Table 11 for both the MN and the SD), W_C^* is the baseline relative channel width (the W_C for the 150 k bulker divided by its length or beam as in Equations 10 and 11 and in Table 10), $(W_C^*)_1$ is the relative channel width for a subject ship (the experimental channel width for a subject ship divided by the length or beam of that ship as in Table 10). Notation for the SD is the same.

The full list of slope values used is presented in Table 11. The missing values represent cases that were not transformed for reasons described below. The results of this transform can be seen in Tables 4 through 9 in Section 3.2, where the observed and transformed MNs are presented together.

The angles between the ship's head and the channel direction in the specified regions suggest a rationale for the application of the two definitions of relative channel width discussed above. Values of the mean and standard deviation of the ship's relative heading in the regions are listed in Table 12. A stronger influence of the ship's <u>length</u> can be anticipated in the waterway regions where the angle of the ship heading, relative to the channel direction, is larger. The turn region is the most extreme case. In the regions characterized by small values of the ship's relative heading, the impact of the ship's <u>beam</u> can be expected to be a dominant factor. Consequently, it is assumed that for the turn region, Definition A (length) is valid, and for the turn-recovery and recovery regions, Definition B (beam) is valid. (The impact of the channel width in the entry region was minimal and the data were not transformed.)

TABLE 11. SLOPE-MN AND SLOPE-SD USED IN TRANSFORMATION TO CONSTANT RELATIVE CHANNEL WIDTH

WATERWAY	Wc/L		Wc/B	
REGION	SLOPE MN	SLOPE SD	SLOPE MN	SLOPE SD
TURN	-0.211E+00	0.176E+00	-	-
TURN-RECOVERY	-0.843E-01	-0.420E-01	-0.200E-01	-0.520E-02
ENTRY	-	-	-	-
RECOVERY	-0.291E-01	0.774E-01	-0.360E-02	0.958E-02

TABLE 12. SHIP'S RELATIVE HEADING IN SELECTED REGIONS

REGION	MN (ψ) [deg]	SD (ψ) [deg]
Turn	-17.7	4.1
Turn-Recovery	-5.9	2.0
Entry	0.7	0.6
Recovery	-1.3	0.7

These assumptions determined the transfcı… done on the experimental data for the development of the regression formulas for ship size that are described in Section 4. These assumptions also determined the selection of the regression formulas describing the dependence of performance on channel width that will be incorporated into the revision of the Waterway Design Manual as described in Section 6.

4.0 DEVELOPMENT OF THE REGRESSION MODELS

4.1 OVERVIEW OF THE APPROACH

The major effort in this analysis was invested in developing regression models for the Group A regions, those involving the greater use of the rudder and the greater perceived risk. Initially, two- and three-coefficient forms were considered as follows:

$$(MN_0, SD_0) = C_1 + C_2 \cdot f_1(I_1) \qquad (14)$$

$$(MN_0, SD_0) = C_1 + C_2 \cdot f_2(I_1) + C_3 \cdot f_3(I_2) \qquad (15)$$

where: (MN_0, SD_0) means MN_0 or SD_0,
C_1, C_2, and C_3 are regression coefficients,
I_1, I_2, and I_3 are selected indices of inherent controllability, and
$f_1()$, $f_2()$, and $f_3()$ are arbitrarily-selected functions.

The final forms of the regression models and the final indices of inherent controllability were selected using several criteria. The correlation coefficient was used as an indicator of effectiveness of the singular indices as well as of the Forms (14) and (15). Potential indices were evaluated first for their correlation with the dependent measures, MN_0 and SD_0, described in Section 3.2. Indices with the highest correlation coefficient were considered in the development of the regression models. The model forms, including the singular indices, with the greatest values of the correlation coefficient were examined for the regularity of the scatter of data-points along the regression line. The regression model having the most regular scatter was finally selected. The potential indices involved in that form were used as the indices for the waterway region.

Special properties of the problem being investigated were used for additional validation of the selected models. Specific demands are made on the ships inherent controllability in each region of the waterway. To be acceptable, the model, with its selected indices, had to be consistent with the demands of the region. Since MN_0 and SD_0 are different measures of the same performance, both models had to be acceptable. Models selected for the successive regions had to reflect the changes in importance of the specific qualities of inherent controllability. The description in Section 3.2 of performance in each waterway region provides a preparation for the description in this section of the application of these additional criteria in the development of the regression models.

Estimations of the MN and SD for the Group B regions, regions associated with minimal rudder use and minimal perceived risk, were based only on the ship's dimensions. The functional models were

selected from the following forms:

$$(MN_0, SD_0) = C_1 + C_2 \cdot (DISPL/10{,}000) \qquad (16)$$

$$(MN_0, SD_0) = C_1 + C_2 \cdot LN\,(DISPL/10{,}000) \qquad (17)$$

$$(MN_0, SD_0) = C_1 + C_2 \cdot L \qquad (18)$$

$$(MN_0, SD_0) = C_1 + C_2 \cdot B \qquad (19)$$

where: (MN_0, SD_0) is a notation for "MN or SD",
C_1, C_2 are the regression coefficients,
$DISPL$ is the ship's displacement in Long Tons (divided by 10,000 to reduce the number of places),
$LN()$ is the natural logarithm of a variable in the parenthesis,
L is the ship's length between perpendiculars,
B is the ship's beam (molded).

4.2 MODELS FOR THE GROUP A REGIONS: TURN, TURN-RECOVERY, RECOVERY, AND ENTRY

4.2.1 Dependence of Performance on Indices of Inherent Controllability

It was assumed that the ship's inherent controllability would make a considerable contribution to the ship's performance in regions where the rudder deflections were meaningfully greater than zero. The turn, turn-recovery, recovery, and entry regions were characterized by such activity of the rudder. Representative values of maximal deflections of the rudder in these regions are shown in Figure 16. Rudder deflections in these regions are all in a range that might be expected to demonstrate the effect of ship's controllability, however they differ substantially from each other. The rudder was deflected up to 35 degrees in the turn region; the deflections in the recovery region were to 8 degrees.

The rudder operations were also qualitatively different in these regions. The turn region can be characterized by a constant rudder deflection. In the turn-recovery region, the maximal value of the rudder deflection is comparable with that in the turn region, but the deflection varies with time. The entry region and, especially, the recovery region, are associated with the dynamic application of moderate rudder deflections.

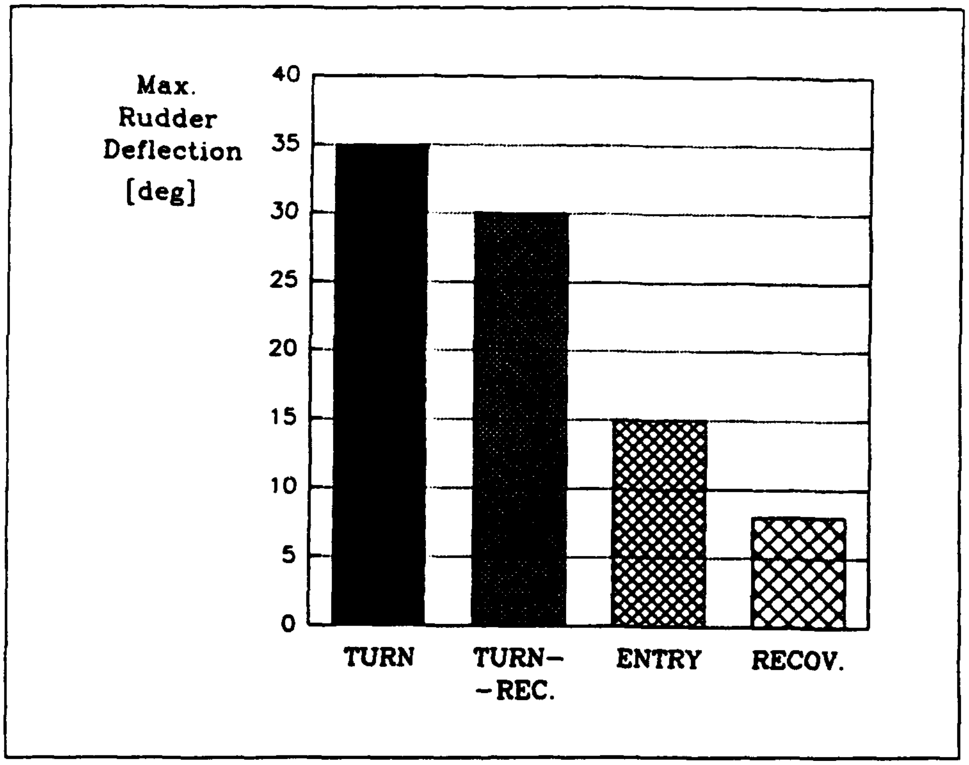


FIGURE 16. MAXIMAL RUDDER DEFLECTIONS BY WATERWAY REGION

These quantitative and qualitative differences of the rudder activity in these regions allow for a verification of the fundamental assumption that inherent controllability has a substantial impact on shiphandling in restricted waterways. The verification was based on the data for 150 k bulk carrier. The three versions of that ship used in the experiment differ only in the rudder size. Hence, the inherent controllability is the only factor that can explain differences in the recorded performance of those ships. Comparisons of the SD and MN values of the crosstrack position for the extreme points of the ship's contour are presented in Figures 17 and 18, respectively.

The extreme points (vertices of the ship's simplified contour) considered here, and their MN and SD values were determined by the procedures described in Section 3. In each region, proportional scales for MN and SD are used. The MN and SD values for the 150 k with degraded rudder are taken as 100% and MNs and SDs for the remaining ship versions are scaled proportionally. In the turn region, two extreme points are considered. MNs and SDs for Point 1 and for Point 3 of the ship's contour are scaled proportionally to the MN and SD determined for Point 3. In each of the remaining three regions, the single extreme point most exposed to grounding is considered. The proportional scale allows direct quantitative evaluation of the importance of controllability.

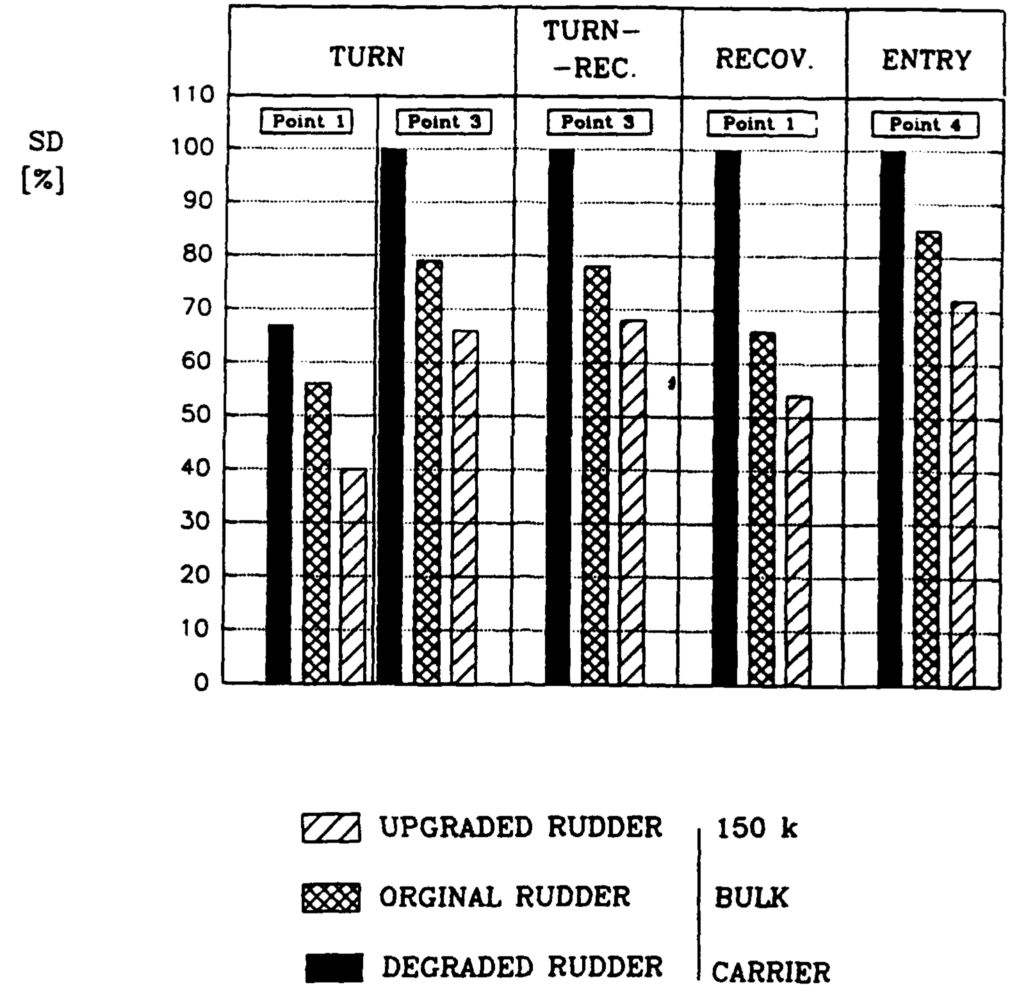


FIGURE 17. SD OF MAX. CROSSTRACK POSITION OF EXTREME POINTS

For the 150 k bulk carrier with the upgraded rudder, 28% to 46% reductions of the SD were observed in all regions, as illustrated in Figure 17. This effect means that the uncertainty of the ship's crosstrack position was remarkably reduced and the safety of navigation was correspondingly improved. In the turn region, the SD for the ship's stern (Point 3) remained greater than that for the bow (Point 1), but both of them decreased with the use of the upgraded rudder. The relatively small reduction of the SD in the entry region can be explained by the pilot's relative insensitivity to crosstrack position resulting from his perception of negligible risk in the region. Measured MN values demonstrated

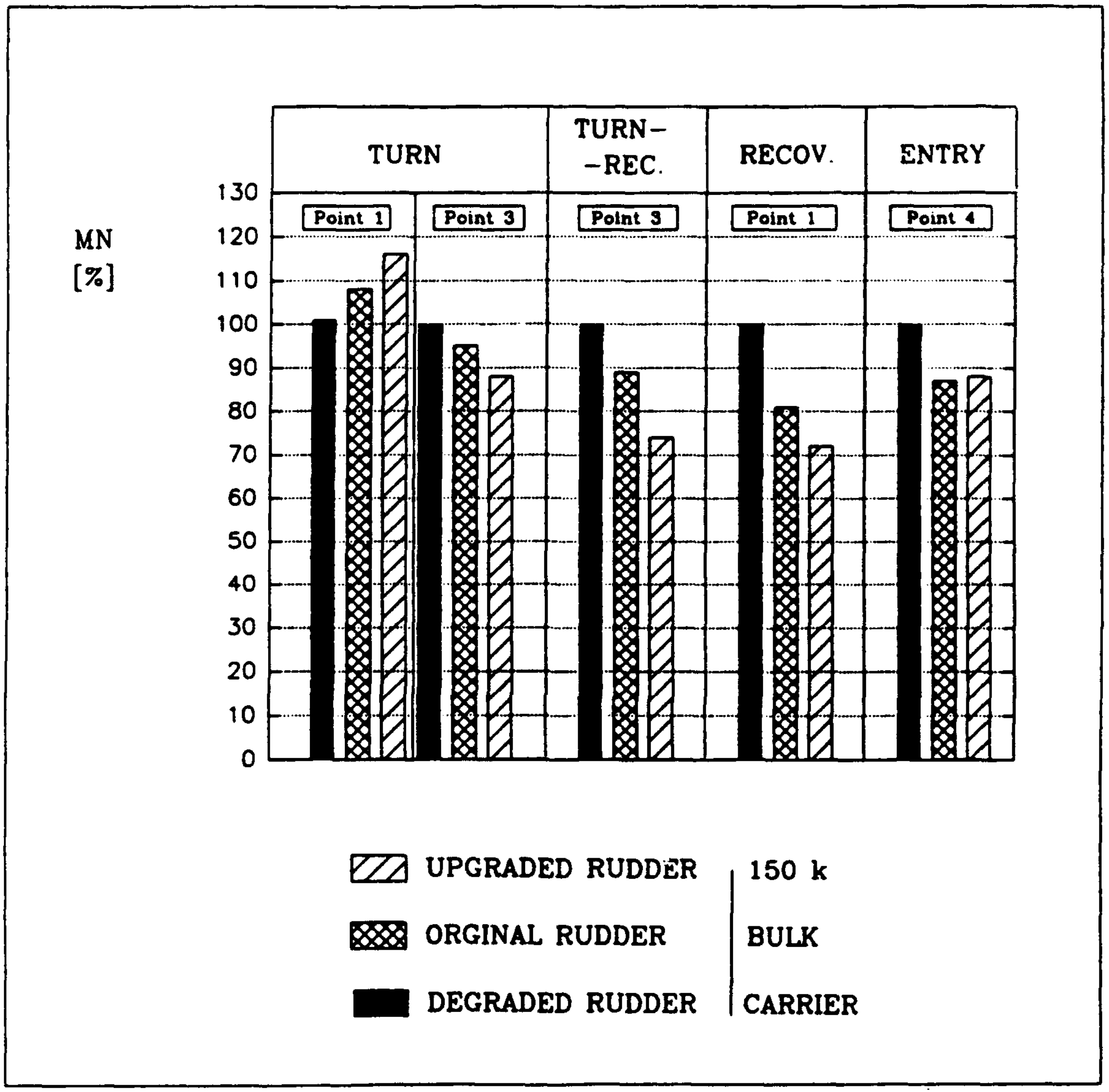


FIGURE 18. MN OF MAX. CROSSTRACK POSITION OF EXTREME POINTS

generally less sensitivity to the inherent controllability than corresponding SD values; however, the latter sensitivity was also impressive. Changes in the MN apparent in Figure 18 are 12% to 28%. A unique situation can be observed in the turn region. The MN for the extreme Point 1 (bow) increased for the more controllable ships, while the MN for Point 3 (stern) was reduced. Those trends demonstrate the pilot's effort to make the turn and, especially, to protect the stern. The pilot wanted to increase the crosstrack distance from the centerline toward the inside of the turn. (See Figure 6.) This was the exceptional situation for the considered regions. In all other regions, the pilot was working to decrease the crosstrack distance to the centerline. In the entry region, the lack of positive difference in MN between the original and the upgraded rudder versions can be explained by the pilot's insensitivity to crosstrack position, as was the case for the SD. Identical trends were observed for the ship's center of gravity. An example of the SD_0 values (in the proportional scale) is shown in Figure 19.

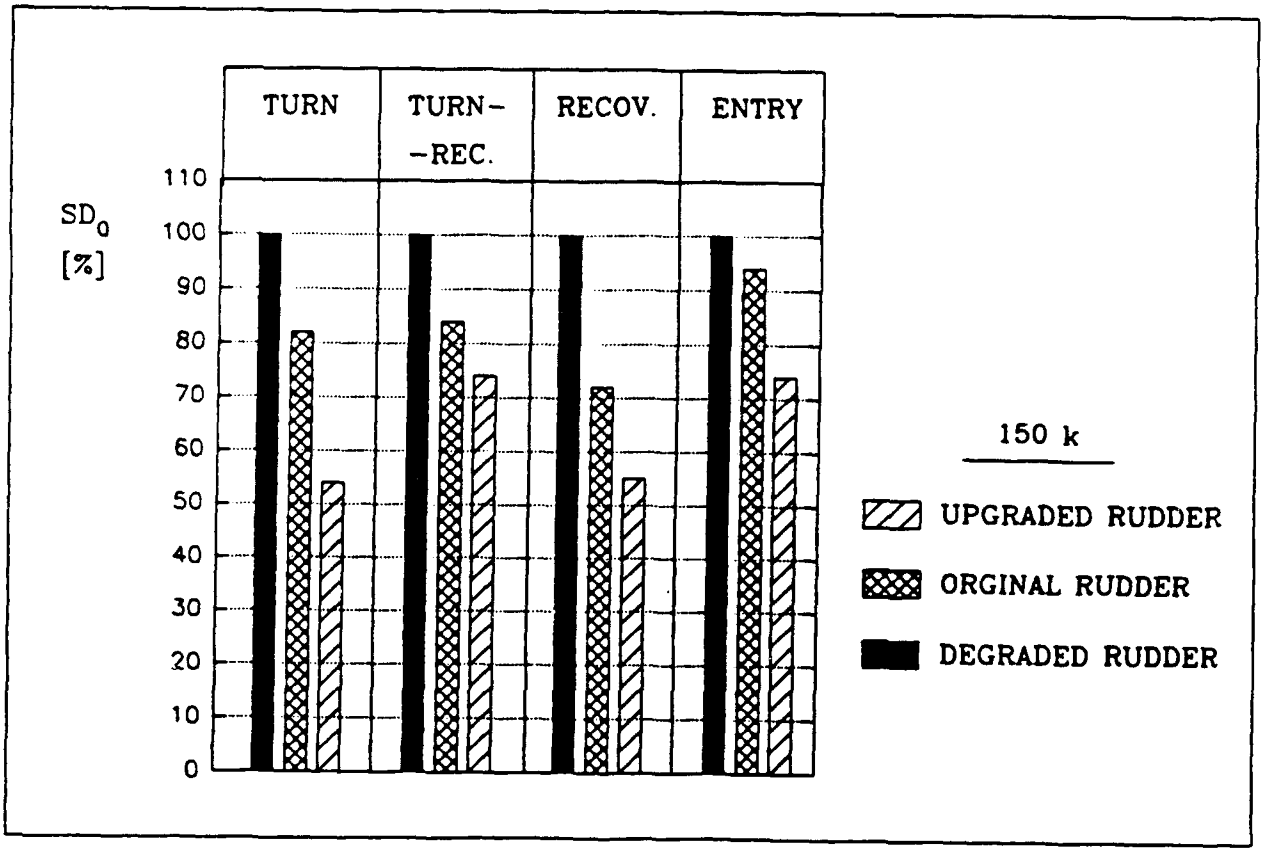


FIGURE 19. SD (PROPORTIONAL) FOR MAX. CROSSTRACK POSITION OF CG

According to the above verification, results of shiphandling described by MN and SD values for the crosstrack position of the ship's contour extreme points (vertices) are meaningfully related to the ship's inherent controllability in the considered waterway regions. Consequently, it was reasonable to develop regression models for the dependence of the MN and SD on selected indices of inherent controllability. The development was based on the selected data for all **seven ships** involved in the experiment.

The Pearson correlation coefficient, $R_{x,y}$, was used as a measure of association between MN_0 (and/or SD_0) and potential indices of the ship's inherent controllability in each region. Correlations determined for the tactical diameter and for Nomoto indices, K and T, in all considered regions are shown for MN_0 in Figure 20, and for SD_0 in Figure 21. Correlations (MN_0*, D*) and (SD_0, D) decrease substantially from the turn region to the recovery region. The opposite trend can be observed in the case of correlations (MN_0, T), (MN_0, K), or (SD_0, T) and (SD_0, K). Those findings correspond very well with the described quantitative and qualitative differences of the rudder activity in the considered regions (Figure 16).

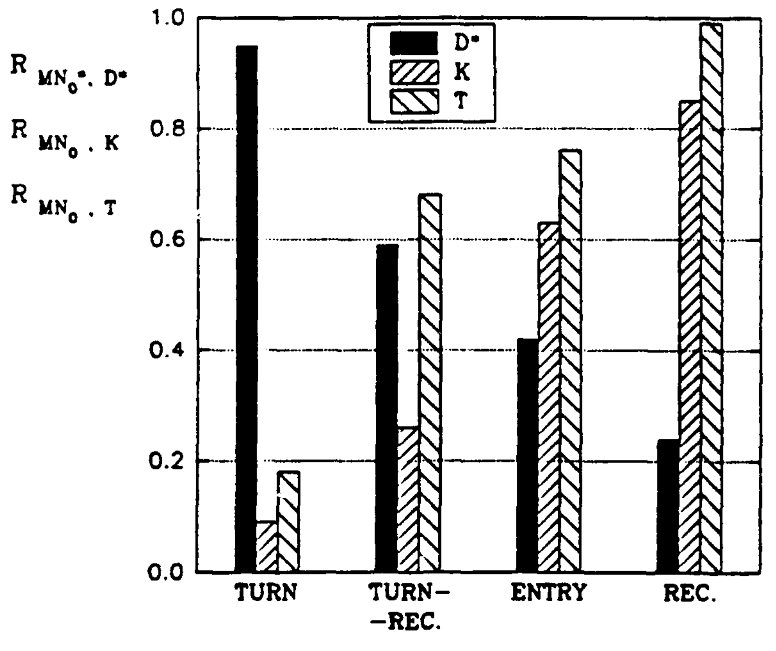


FIGURE 20. CORRELATIONS BETWEEN MN_0 AND INDICES BY REGION

Very high correlations for (MN_0*, D*) and (SD_0, D) (r = 0.98 and 0.945, respectively) confirm that D* and D accurately predict the ship's turning ability in the turn region. Predominance of the quick response to steering (Index T) in the remaining regions is the result of dynamic changes of the rudder deflection. Consequently, the regression models for the turn-recovery, the recovery, and for the entry regions were developed together, independently of the model for the turn region.

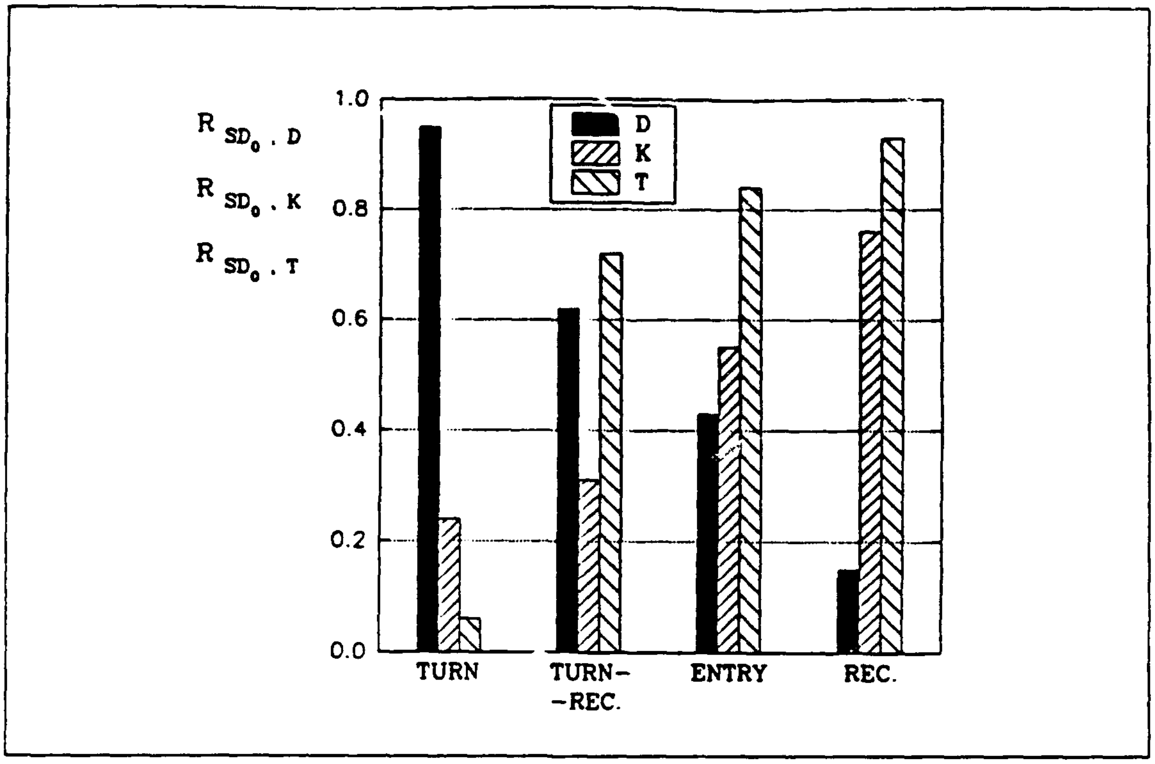
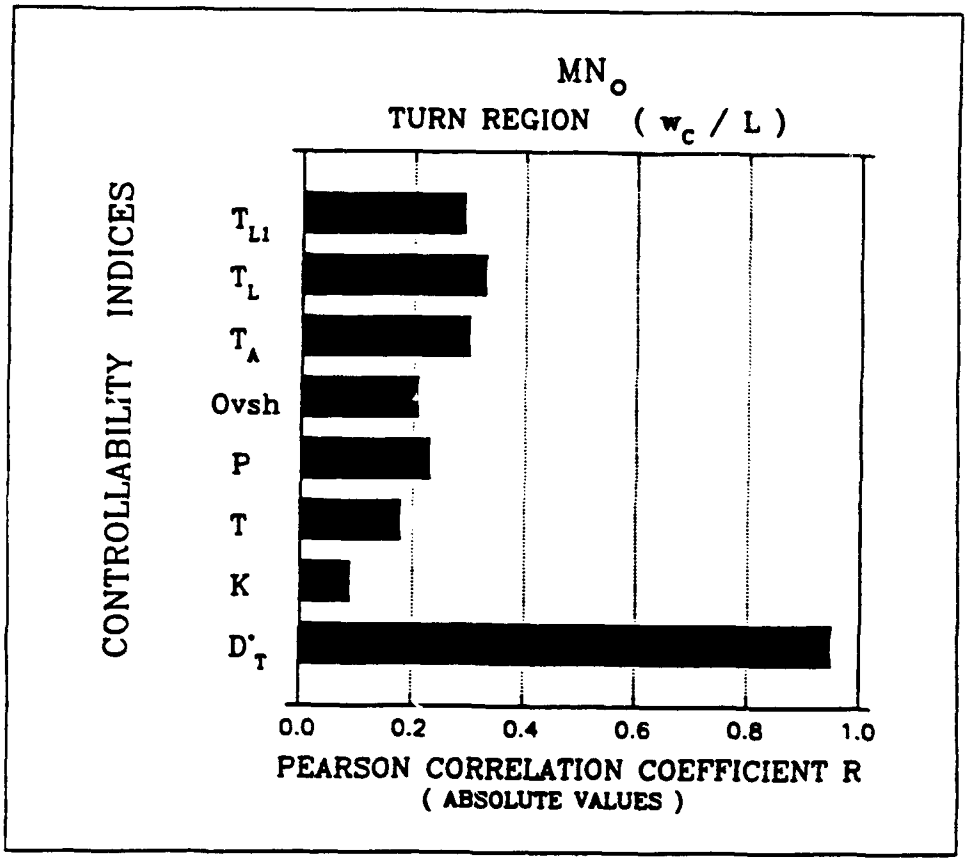


FIGURE 21. CORRELATIONS BETWEEN SD_0 AND INDICES BY REGION

4.2.2 Regression Models in the Turn Region

The correlations between performance and each of the potential indices of the ship's inherent controllability are shown in Figures 22 and 23 for MN_0 and SD_0, respectively. In both cases, not only is the tactical diameter very highly-correlated with performance, but no other index shows a very high correlation. Consequently, further development of the model for the turn region was limited to the functions of one independent variable: the tactical diameter. The linear functions showed the most-adequate to almost-ideal values of the correlation coefficients. The following models were selected:



where:

MNo, SDo	are the mean and standard deviation values for the position of the ship's center of gravity,
*	is a notation for a non-dimensional parameter,
D_T	is the tactical diameter,
T, K	are the indices proposed by Nomoto,
P	is the index proposed by Norrbin,
Ovsh	is the first overshoot angle,
T_A	is the time to reach the first execute heading change,
T_L	is the course lag time according to Nomoto,
T_{L1}	is the course lag time for the first overshoot.

FIGURE 22. CORRELATIONS BETWEEN MN$_0$ AND INDICES

$$MN_0^* = C_1 + C_2 \cdot D_T^* \tag{20}$$

$$SD_0 = C_1 + C_2 \cdot D_T \tag{21}$$

where:
MN_0 and SD_0 are the mean and standard deviation values for the position of the ship's center of gravity,
D_T is the tactical diameter,
$*$ is a notation for a nondimensional parameter,
C_1 and C_2 are the regression coefficients.

The scatter plots are shown in Figures 24 and 25. The following convention has been adopted for plotting symbols of the ships:

1 33 k bulk carrier,
2 1000 ft Great Lakes carrier,
3 76 k bulk carrier,
4 150 k bulk carrier - original rudder,
5 150 k bulk carrier - degraded rudder,
6 150 k bulk carrier - upgraded rudder,
7 250 k tanker.

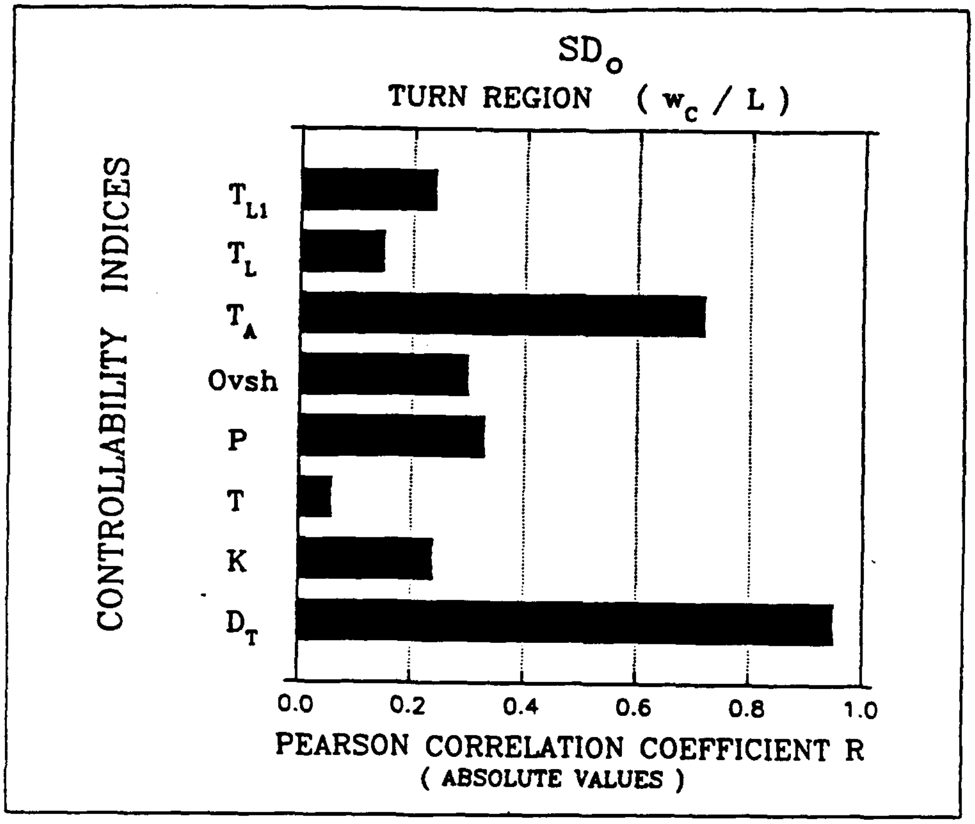


FIGURE 23. CORRELATIONS BETWEEN SD_0 AND INDICES

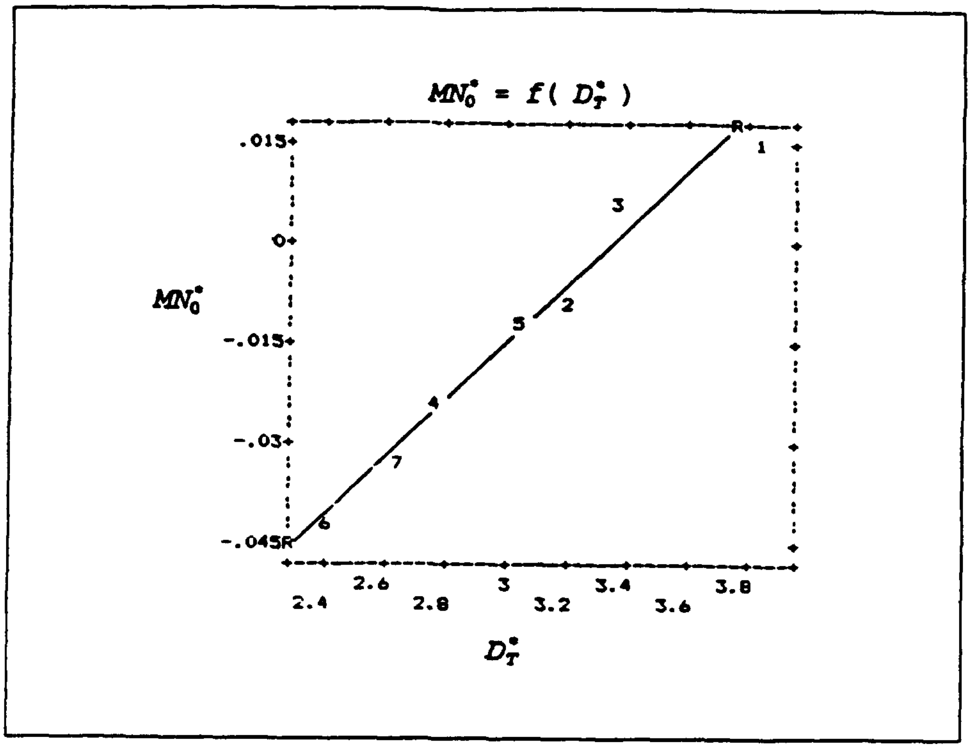


FIGURE 24. RELATION BETWEEN MN_0* AND D_T*, AND LINEAR MODEL

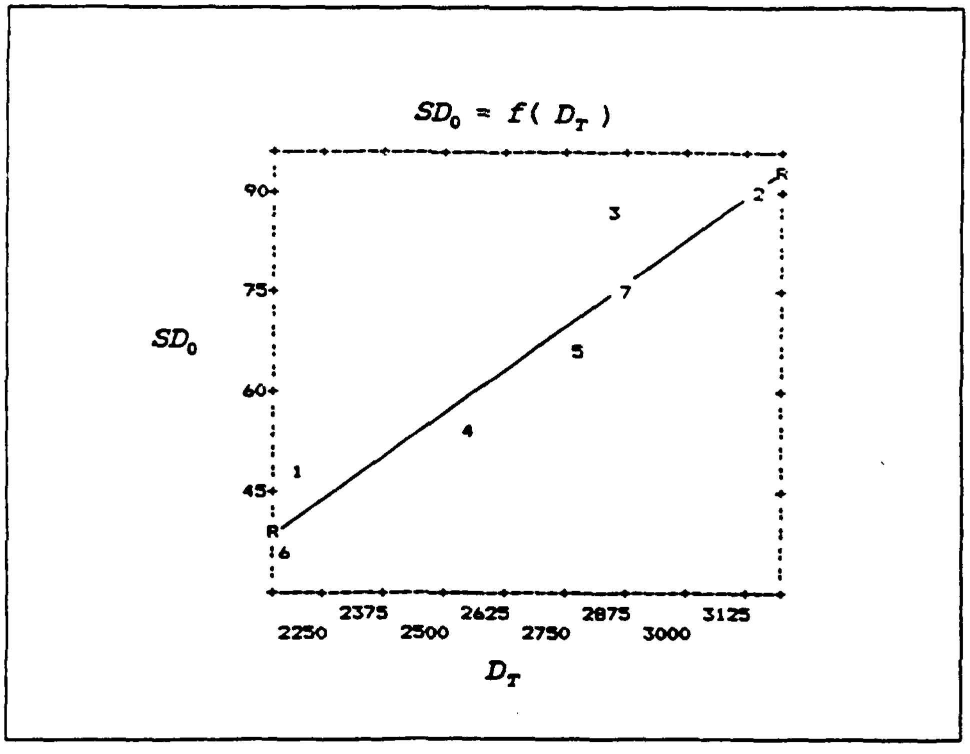


FIGURE 25. RELATION BETWEEN SD_0 AND D_T, AND LINEAR MODEL

Basic statistics for the models (20) and (21) are shown in Table 13. The following parameters were considered:

- R the multiple R, a square root from the coefficient of determination,
- BETA the standardized regression coefficients,
- F the F statistic for the regression model,
- PR>F the observed significance level (for F),
- t t-value for each coefficient in the regression model,
- PR>|t| the two-tailed observed significance level (for t).

It was concluded that both models fully satisfied all requirements. The correlations with the experimental data are substantial. The data points are scattered regularly along the regression lines. Contribution of the tactical diameter to the final results is equal to the multiple R. The null hypotheses for the regression coefficients (that they are equal to zero) are rejected at a significance level of 0.01.

TABLE 13. STATISTICS FOR SELECTED REGRESSION MODELS

REGION	STAT.	MN* = f(D*)		SD = f(D)	
		C1	C2 D*	C1	C2 D
TURN	R	0.98		0.94	
	BETA	-	0.98	-	0.95
	F	124.6		41.8	
	PR>F	0.0001		0.0013	
	t	-12.3	11.2	-3.45	6.45
	PR>|t|	.0001	.0001	.0182	.0013
	C1	-0.13899		-75.94133	
	C2	0.04107		0.05307	

The selected models (20) and (21) use the tactical diameter as an index of the ship's turning ability. The nondimensional MN_0 is associated with the nondimensional tactical diameter. However, in the SD_0 model, the dimensional parameters are employed. This difference reflects the opposite trends in correlations presented in Figure 26. MN_0 is negligibly correlated with D_T R = 0.10), but $MN_0{}^*$ is almost perfectly-determined by $D_T{}^*$ (R = 0.98). This strong discrimination between the dimensional and nondimensional forms of the same parameters seems consistent with pilots' reports of their activities. Pilots tend to describe the situation in terms of such nondimensional parameters as multiples of ship length, rarely describing distances in feet. If the pilots initiated "hard rudder" at the same number of ship lengths before the turn point for each ship, the observed correlation of 0.98 between the nondimensional forms could result. SD_0 is less directly-controlled by the pilots, but is determined by both the extent of agreement among the pilots as to the intended maneuver through the turn and random variation in their success in implementing those intentions. Therefore, the dominance of the nondimensional form is not apparent there. However, the strong correlations of SD_0 with both D_T (R = 0.95) and $D_T{}^*$ (R = 0.79) imply that tactical diameter is the determining parameter for this measure as well.

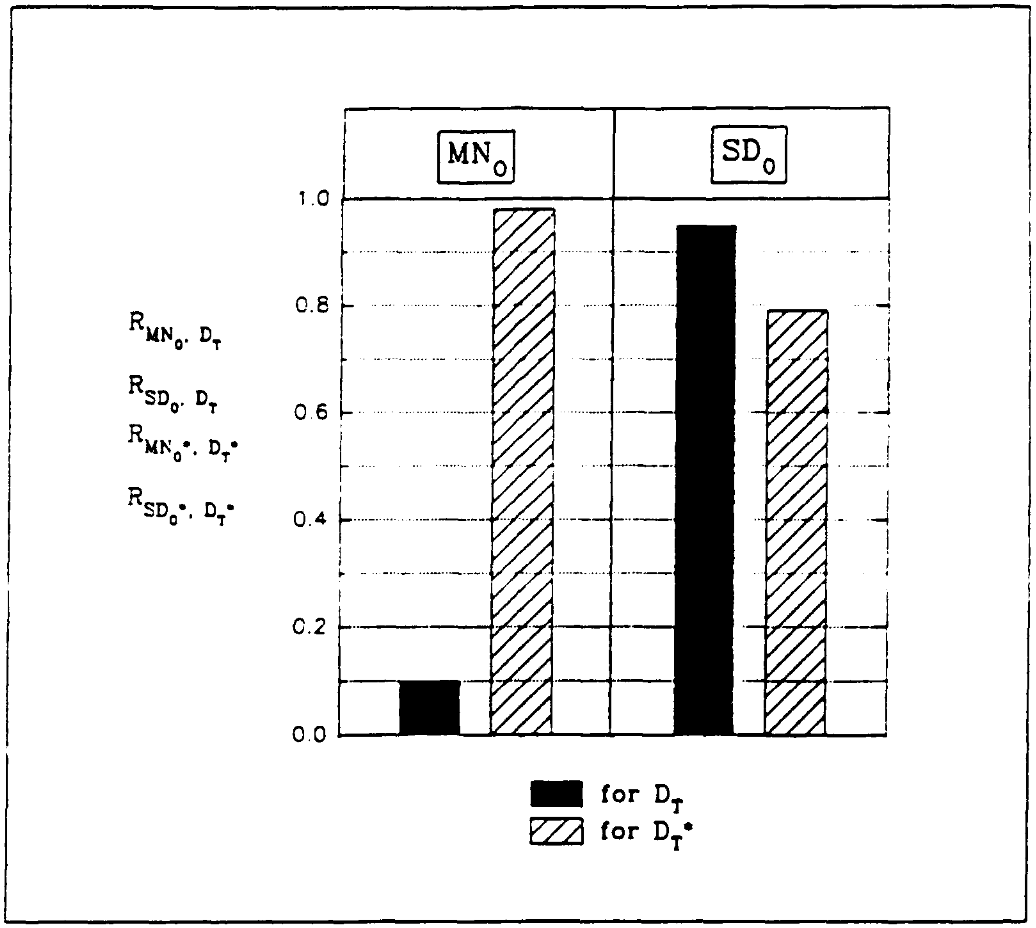


FIGURE 26. CORRELATIONS OF MN_0 AND SD_0 WITH TACTICAL DIAMETER

4.2.3 Regression Models in the Turn-recovery, Recovery, and Entry Regions

The piloted performance data for the turn-recovery, recovery, and entry regions were characterized by dynamic application of the rudder: that is, frequent changes in direction and amount of rudder. This rudder use implies a meaningful impact of the ship's turning ability and, especially, a substantial contribution of the quickness of response to steering (Figure 20). Hence, the domain of adequate models for the relations between inherent controllability indices and piloted performance cannot be one-dimensional as was the case for the turn region; it must be at least two-dimensional. The two-dimensional domain {K*, T*}, used in the selection of ship models for the simulator experiment (Smith et al., 1990), is shown in Figure 27. The figure shows a long, narrow envelope that encloses observed values of K* and T* for commercial ships (Nomoto and Norrbin, 1969; Barr et al., 1981).

The ship models for the experiment were selected primarily along the mean curve marking the center of the envelope (in Figure 27, Ships 1, 3, 4, 7), but also at the edges of the envelope (in Figure 27, Ships 2, 5, 6). The intention, during the design of the experiment, was to sample both the mean curve and extreme values. Because of this sampling, functions developed from the resulting data are assumed to be representative of the entire envelope.

Correlations between MN_0 (and SD_0) and each of the potential indices of the ship's inherent controllability are shown in Figure 28. The same trends are observed for all the considered regions. The tactical diameter has lost the superiority of correlation with MN_0 and SD_0 that it had in the turn region. Here, the indices T, T_L, and T_{L1}, representing quickness of response to steering, have the superior correlations. The tactical diameter has also lost its position as an index of the turning ability to the index K. These trends result from the differences in the rudder activity in the successive regions (Figure 16), and the specific qualities of Nomoto indices K and T (Section 2). The relatively-poorer effectiveness of the Norrbin index, P, and of the "time to reach the first execute heading change" (T_A) are apparent also.

Because of these observed trends, investigations of regression models for the relations between indices of inherent controllability and piloted performance were limited to fourteen two-variable functions, based on the following pairs of the potential indices: (K, T), (D, T), (Ovsh, T_A), (Ovsh, T_L), (Ovsh, T_{L1}). After preliminary evaluation, the following forms of the regression models were selected for further investigation:

$$(MN_0, SD_0) = C_1 + C_2 \cdot K + C_3 \cdot T \tag{22}$$

$$(MN_0^*, SD_0^*) = C_1 + C_2 \cdot 1/K^* + C_3 \cdot \ln(T^*) \tag{23}$$

$$(MN_0^*, SD_0^*) = C_1 + C_2 \cdot \ln(K^*) + C_3 \cdot \ln(T^*) \tag{24}$$

$$(MN_0, SD_0) = C_1 + C_2 \cdot 1/K + C_3 \cdot \ln(T) \tag{25}$$

$$(MN_0, SD_0) = C_1 + C_2 \cdot D_T + C_3 \cdot \ln(T) \tag{26}$$

$$(MN_0, SD_0) = C_1 + C_2 \cdot Ovsh + C_3 \cdot T_{L1} \tag{27}$$

where:
MN_0 and SD_0 are the mean and standard deviation values for the position of the ship's center of gravity,
$*$ is a notation for a nondimensional parameter,
D_T is the tactical diameter,
T and K are the indices proposed by Nomoto,
$Ovsh$ is the first overshoot angle,
T_{L1} is the course lag time for the first overshoot,
C_1, C_2, and C_3 are the regression coefficients.

Basic statistics for the Models (22) to (27) are shown in Table 14 (for MN_0) and in Table 15 (for SD_0). The following parameters were considered:

- R the multiple R, a square root from the coefficient of determination,
- BETA the standardized regression coefficients,
- F the F statistic for the regression model,
- PR>F the observed significance level (for F),
- t t-value for each coefficient in the regression model,
- PR>|t| the two-tailed observed significance level (for t).

The statistics presented here show that all the models considered are best in describing relations in the turn-recovery region. There, multiple R values are highest and significance levels of the F and t statistics are smallest. The poorest results are in the entry region, presumably, because of the pilot's relative insensitivity to position and risk there. Models based on the nondimensional parameters are poorer than those based on dimensional ones. The multiple Rs are smaller and the observed significance levels of the F and t statistics are unacceptably high. The inadequacy of the nondimensional versions is apparent for both the MN_0 and the SD_0 models. For the turn region, the effectiveness of nondimensional parameters was attributed to pilot mechanisms. In the present regions, the pilot attempted to minimize the ship's crosstrack position and yaw movement by dynamic use of the rudder. Minimalization of the crosstrack position does not require distance estimations relative to ship length, as does the active position

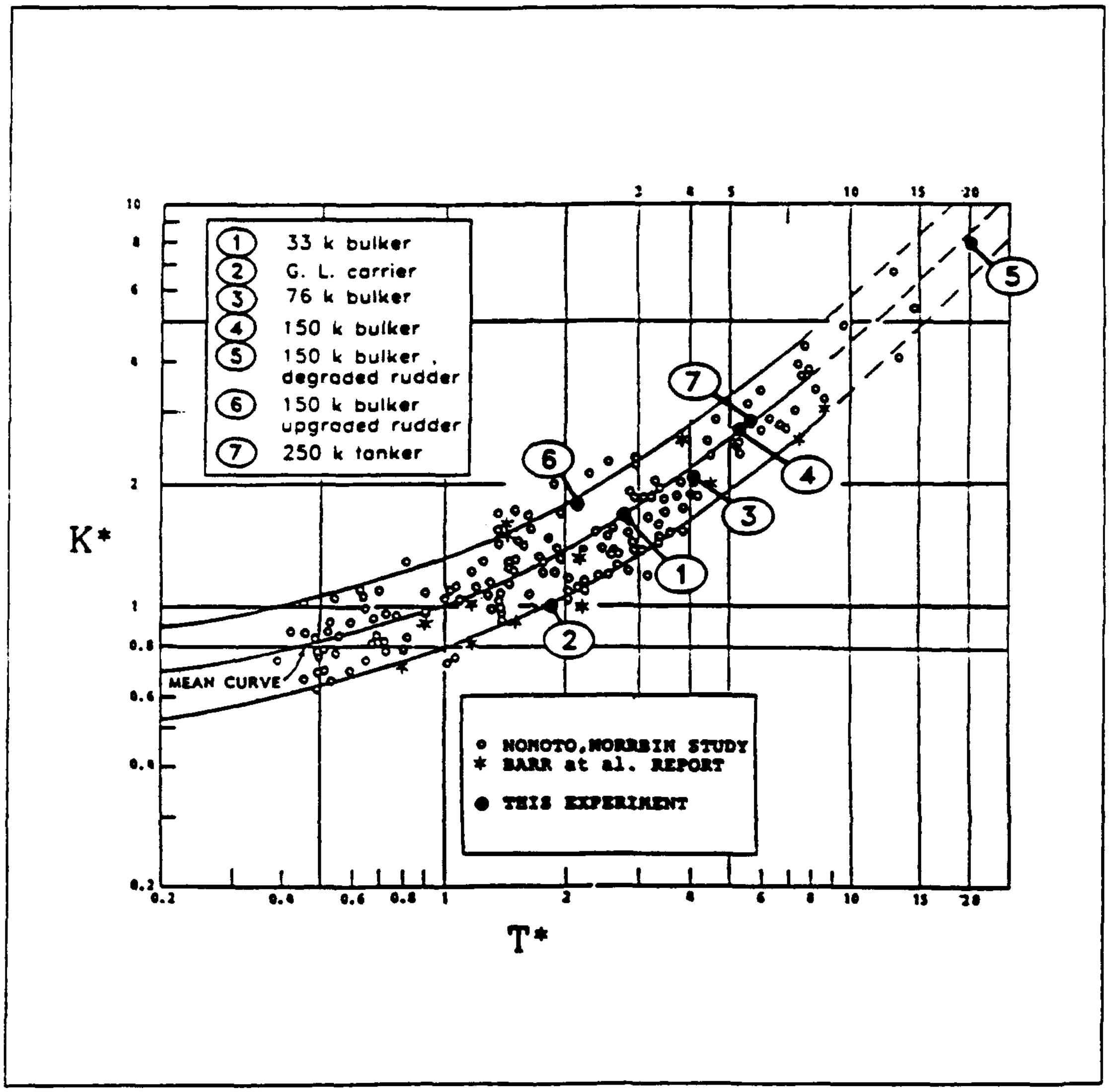


FIGURE 27. RANGE OF INHERENT CONTROLLABILITY QUALITIES

change in the turn region. Therefore, apparently, the nondimensional parameters (nondimensionalized by ship length) do not have the effectiveness that they had in the turn region. (Note in Section 3.3, Table 12 that crab angles at the ship's extreme crosstrack positions were small, allowing any possible estimations of distances to be made relative to the ship beam. For this reason the performance data in these regions have been transformed to the same channel width relative to the ship's beam.)

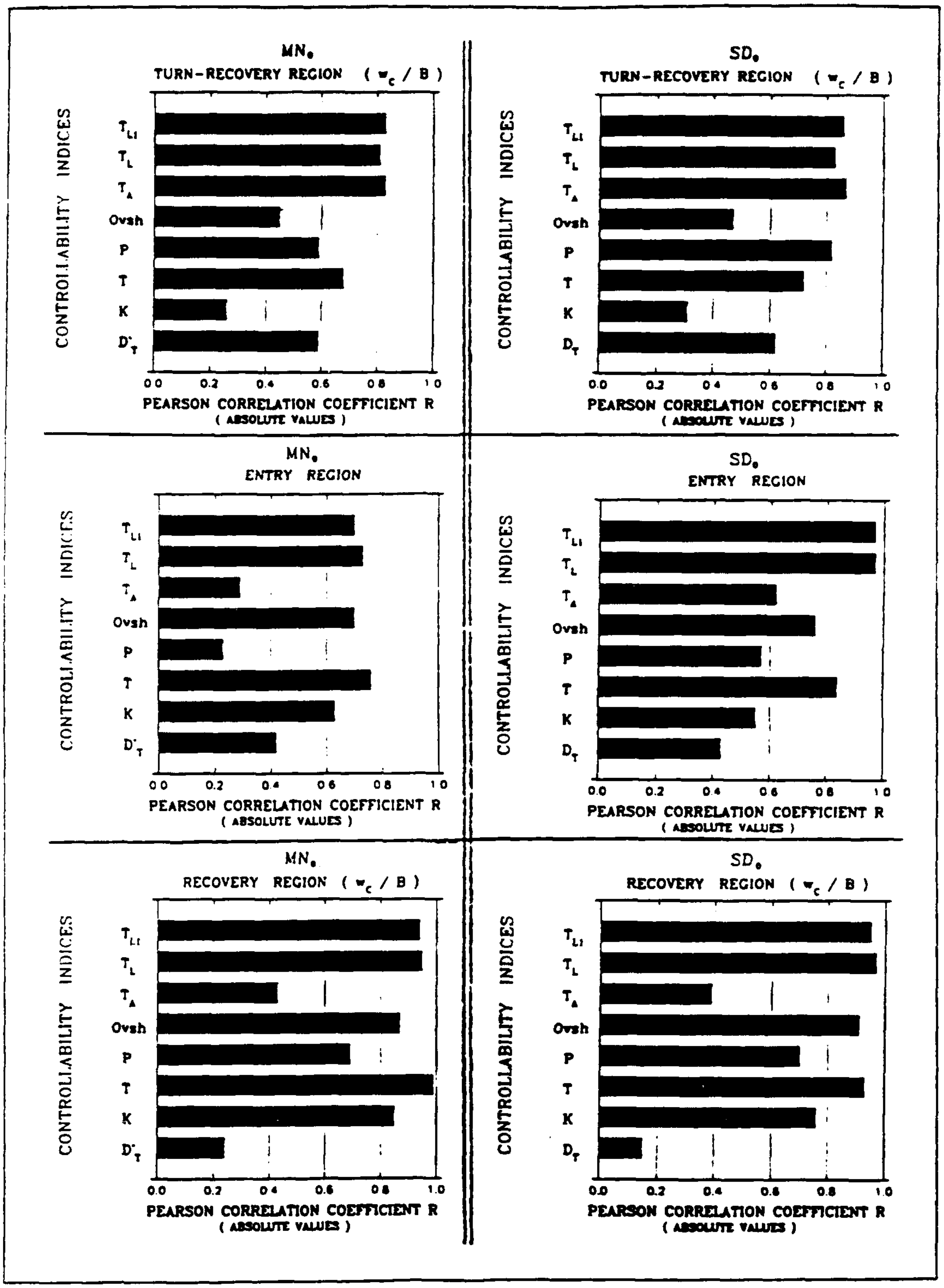


FIGURE 28. CORRELATIONS BETWEEN MN_0 (AND SD_0) AND INDICES

TABLE 14. STATISTICS FOR MN_0 MODELS (22) TO (27)

MNo= f(I)		I																	
REGION	STAT.	K, T			1/K*, ln(T*)			ln(K*), ln(T*)			1/K, ln(T)			D, ln(T)			Ovsh, TL1		
		C_1	K	T	C_1	1/K*	ln(T*)	C_1	ln(K*)	ln(T*)	C_1	1/K	ln(T)	C_1	D	ln(T)	C_1	Ovsh	TL1
TURN--RECOV.	R	0.98			0.79			0.79			0.95			0.87			0.92		
	BETA	-	-1.49	1.99	-	-.004	0.78	-	0.42	0.37	-	0.71	1.25	-	0.38	0.68	-	-0.66	1.37
	F	57.77			3.22			3.35			20.49			6.056			10.64		
	PR>F	0.0011			0.1468			0.1399			0.0079			0.0616			0.025		
	t	15.2	-7.76	10.4	0.82	-.005	0.85	3.23	0.31	0.27	-4.31	3.61	6.36	-2.01	-.005	2.60	2.03	-1.94	4.03
	PR>|t|	.0001	.0015	.0005	.456	.997	.440	.032	.77	.79	.0125	.0225	.0031	.115	0.22	0.06	.112	.124	.016
ENTRY	R	0.76			0.79			0.89			0.78			0.82			0.73		
	BETA	-	0.18	-0.92	-	1.12	0.37	-	-2.5	1.7	-	-.003	-0.78	-	0.26	-0.86	-	-0.38	-0.40
	F	2.81			3.24			7.50			3.11			4.07			2.35		
	PR>F	0.1728			0.1455			0.0443			0.1532			0.1086			0.2117		
	t	-2.37	0.27	-1.36	-1.71	1.22	0.40	1.70	-2.44	-4.45	0.73	-.007	-1.90	0.517	0.867	-2.85	-0.11	-0.65	-0.69
	PR>|t|	0.077	0.80	0.25	0.162	0.29	0.71	0.164	0.071	0.011	0.507	0.99	.1305	0.633	0.44	0.05	0.92	0.55	0.53
RECOVERY	R	0.99			0.95			0.96			0.96			0.96			0.96		
	BETA	-	0.1	-1.1	-	-0.1	-1.1	-	-0.65	-0.32	-	0.07	-0.92	-	0.05	-0.98	-	-0.30	-0.70
	F	152.3			19.5			25.4			26.8			26.7			22.6		
	PR>F	0.0002			0.0087			0.0053			0.0048			0.0048			0.0066		
	t	-1.88	0.76	-8.97	0.37	-0.24	-2.32	-0.32	-1.08	-0.52	3.18	0.40	-5.29	4.37	0.38	-7.09	3.15	-1.29	-2.82
	PR>|t|	0.13	0.49	.0009	0.73	0.82	0.08	0.76	0.34	0.63	0.03	0.71	0.006	0.012	0.72	0.002	0.035	0.266	0.048

TABLE 15. STATISTICS FOR SD_0 MODELS (22) TO (27)

SDo= f(I)		I																	
REGION	STAT.	K, T			1/K*, ln(T*)			ln(K*), ln(T*)			1/K, ln(T)			D, ln(T)			Ovsh, TL1		
		C_1	K	T	C_1	1/K*	ln(T*)	C_1	ln(K*)	ln(T*)	C_1	1/K	ln(T)	C_1	D	ln(T)	C_1	Ovsh	TL1
TURN--RECOV.	R	0.99			0.94			0.90			0.97			0.90			0.94		
	BETA	-	-1.42	1.97	-	0.89	1.74	-	-0.55	1.43	-	0.21	1.27	-	0.42	0.68	-	-0.66	1.39
	F	69.02			16.3			8.85			28.48			8.19			14.79		
	PR>F	0.0008			0.0120			0.034			0.0043			0.0386			0.0142		
	t	22.0	-8.10	11.2	1.85	1.82	3.53	9.57	-0.576	1.50	-4.2	4.2	7.5	1.85	1.82	3.53	4.17	-2.24	4.72
	PR>|t|	.0000	.0013	.0004	0.139	0.144	0.024	.0007	0.595	0.21	0.014	0.013	0.002	0.139	0.144	0.024	0.014	0.089	0.009
ENTRY	R	0.93			0.51			0.56			0.97			0.97			0.97		
	BETA	-	-0.84	1.58	-	0.37	0.84	-	-1.23	1.69	-	0.22	1.10	-	0.17	0.90	-	-0.08	1.03
	F	13.5			0.70			8.93			28.56			27.18			30.7		
	PR>F	0.0167			0.5502			0.4650			0.0043			0.0047			0.0037		
	t	12.5	-2.23	4.19	0.70	0.29	0.66	3.145	-0.67	0.916	-1.29	1.33	6.51	-1.04	1.23	6.59	6.95	-0.36	4.88
	PR>|t|	.0002	0.089	.0138	0.52	0.79	0.55	0.035	0.542	0.412	0.27	0.26	0.003	0.36	0.29	0.003	0.002	0.74	0.008
RECOVERY	R	0.94			0.98			0.98			0.99			0.99			0.98		
	BETA	-	-0.29	1.19	-	-0.52	0.48	-	0.77	0.22	-	-0.11	0.91	-	-0.15	1.03	-	-0.63	0.40
	F	16.3			57.8			56.7			68.8			143.0			42.5		
	PR>F	0.0119			0.0011			0.0012			0.0008			0.0002			0.0020		
	t	3.63	-0.83	3.42	2.88	-1.90	1.77	5.10	1.87	0.53	-3.70	-1.03	8.21	-6.99	-2.52	16.73	-2.2	2.2	3.5
	PR>|t|	0.022	0.45	0.027	0.045	0.130	0.152	0.007	0.14	0.62	0.021	0.36	0.001	0.002	0.065	0.0001	0.09	0.09	0.03

The null hypotheses for the coefficient C_2 (associated with the index K) could not be rejected at a significance level of 0.05 for any of the MN_0 models in the entry and recovery regions. This finding reflects the increased contribution of turning ability, as indexed by K, to shiphandling in those regions (Figure 28) and the limited number of ships selected from the edge of the envelope (Figure 27) with higher values of K. The MN_0 is more sensitive to the outliers in the data sample, than is the SD_0.

Model (22) was selected for both the MN_0 and SD_0 relations in the turn-recovery region. The correlation is superior: R, greater than 0.97. All the null hypotheses could be rejected at significance levels less than 0.0015. Model (22) creates a plane of estimated/predicted values of SD_0 (or MN_0) over the domain {K, T}. As an exploration of this plane, a number of new "ships" with the length of the 150 k bulk carrier (915 feet), but with new combinations of K and T were evaluated. The estimated/predicted performance for these ships is plotted in Figure 29. The new ships, or their K and T values, are represented on the plot by the lower case letters, a, b, c, and d, with the values for the original 150 k bulker at the center of the plane they form. Ship c has the poorest-performing values of both indices; Ship b, the best. The plane of the estimated SD_0 values for the four ships is indicated on the plot by Points A, B, C, and D, with performance for the original values of the 150 k bulker at the center. The decrease in the SD_0 for better qualities of the ship's inherent controllability is apparent and substantial.

Model (22) was selected for the SD_0 relation in the recovery and entry regions, also. Correlations with the experimental data are superior: R, greater than 0.93. Significance levels in the entry region are more convincing than those in the recovery region. Because of the similarity of shiphandling mechanisms in these two regions, statistics were pooled and the null hypothesis for the coefficient C_2 was rejected at a significance level of 0.23. The use of a 0.23 significance level in this specific situation seems reasonable.

Model (22) can be expected to be appropriate for a more extensive sample of experimental data. However, for the available data, the null hypothesis could not be rejected for coefficient C_2 of the MN_0 models in the entry and recovery regions. Consequently, the following model was developed:

$$MN_0 = C_1 + C_2 \cdot T \tag{28}$$

Basic statistics for Model (28) are shown in Table 16. Resulting significance levels are less than 0.05 without any decrease in correlation.

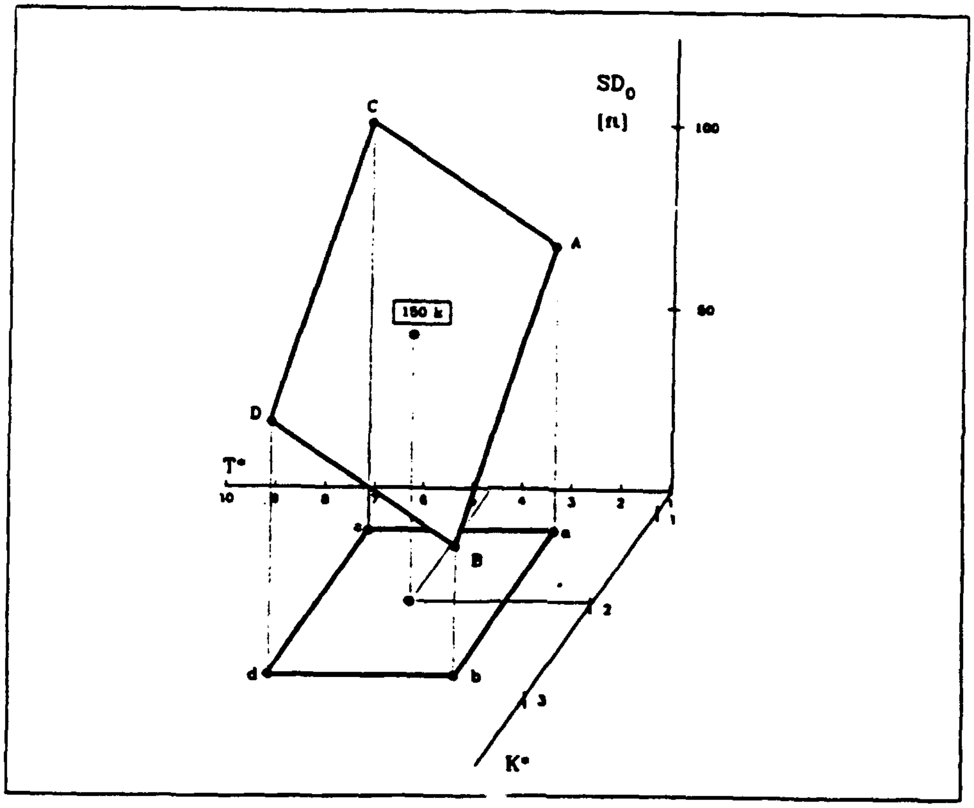


FIGURE 29. SD_0 FOR TURN-RECOVERY AS ESTIMATED BY MODEL (22)

Scatter plots for the all the models selected in this subsection are shown in Figure 30. The plotting symbols for the ships are as follows:

1 33 k bulk carrier,
2 1000 ft Great Lakes carrier,
3 76 k bulk carrier,
4 150 k bulk carrier - original rudder,
5 150 k bulk carrier - degraded rudder,
6 150 k bulk carrier - upgraded rudder,
7 250 k tanker.

Values of the regression coefficients are listed in Table 17.

TABLE 16. STATISICS FOR MN_0 MODEL (28) IN ENTRY AND RECOVERY

$MN_0 = C_1 + C_2 \cdot T$				
STAT.	ENTRY		RECOVERY	
	C1	C2 T	C1	C2 T
R	0.76		0.99	
BETA	-	-0.76	-	-0.99
F	6.8		332.2	
PR>F	0.0476		0.0000	
t	-4.38	-2.61	-2.38	-18.2
PR>|t|	0.007	0.048	.0628	.0000

TABLE 17. REGRESSION COEFFICIENTS FOR MODELS (22) AND (28)

REGION	COEFF.	MNo=f()	SDo = f()
TURN--RECOV.	C1	157.95821	83.45509
	C2	-4342.34592	-1641.49913
	C3	0.38945	0.15277
ENTRY	C1	-33.29522	28.50342
	C2	-0.06275	-273.81914
	C3	-	0.02454
RECOVERY	C1	-2.93654	28.70576
	C2	-0.07095	-352.33160
	C3	-	0.09754

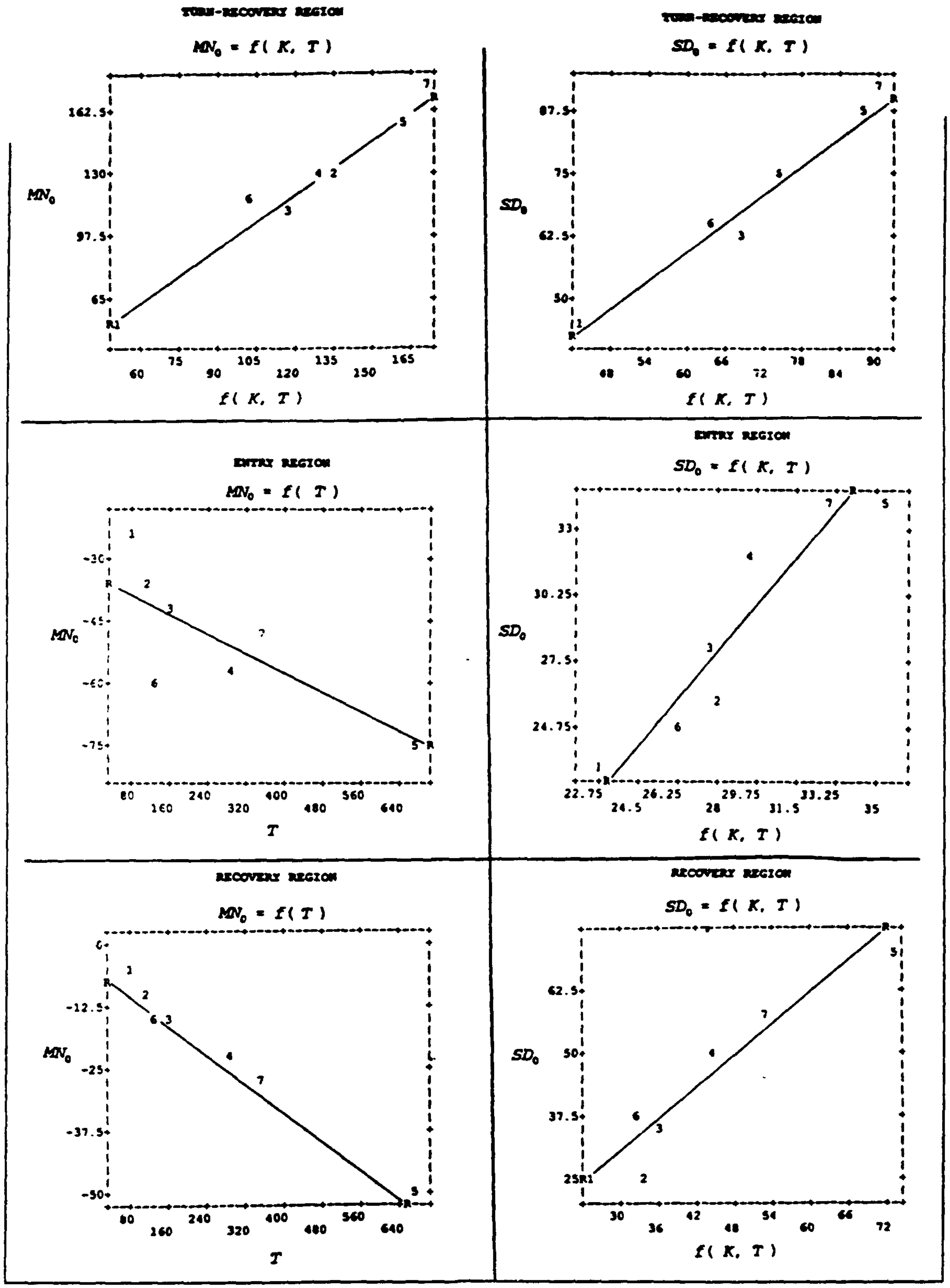


FIGURE 30. SCATTER PLOTS FOR THE SELECTED MODELS

4.3 MODELS FOR THE GROUP B REGIONS: TURN-ENTRY AND TRACKKEEPING

4.3.1 Regression Models in the Turn-Entry Region

The models for the turn-entry region were selected from the general forms presented as (16) through (19) in Section 4.1. Correlation of the potential models with measures of piloted performance are presented in Table 18. Based on these correlations, the model using the beam as independent variable was selected for this region. A strong impact of the ship's beam on the pilot's subjective decisions can be logically expected with small crab angles of 3 degrees or less. The scatter plots for the relation of the ship's beam to the measured MN_0 and SD_0 are shown in Figures 31 and 32, respectively. The plotting symbols for the ships are as follows:

1 33 k bulk carrier,
2 1000 ft Great Lakes carrier,
3 76 k bulk carrier,
4 150 k bulk carrier - original rudder,
5 150 k bulk carrier - degraded rudder,
6 150 k bulk carrier - upgraded rudder,
7 250 k tanker.
("$" represents the superposition of two ships.)

The statistics and the regression coefficients for this relation are presented in Table 19. The following models were selected:

$$MN_0 = 148.5 - 0.734 \cdot B \qquad (29)$$

$$SD_0 = 71.7 - 0.185 \cdot B \qquad (30)$$

where: B is the ship's beam (molded) [ft].

TABLE 18. CORRELATIONS FOR MODELS (16) TO (19) IN TURN-ENTRY

Waterway region:		ENTRY.			
No	f (I)	R(MN)	R(MN*)	R(SD)	R(SD*)
1	DISPL/10,000	0.78	--	0.34	--
2	LN(DISPL/10,000)	0.81	--	0.34	--
3	L	0.34	--	0.05	--
4	B	0.85	--	0.43	--

MN and SD are the Mean and Standard Deviation values for the position of the ship's geometric center.
R( ) is the correlation coefficient of ( ).
* is a notation for non-dimensional parameter.

DISPL is the ship's displacement [Long Tons].
L is the ship's length between perpendiculars [ft].
B is the ship's beam (molded) [ft].

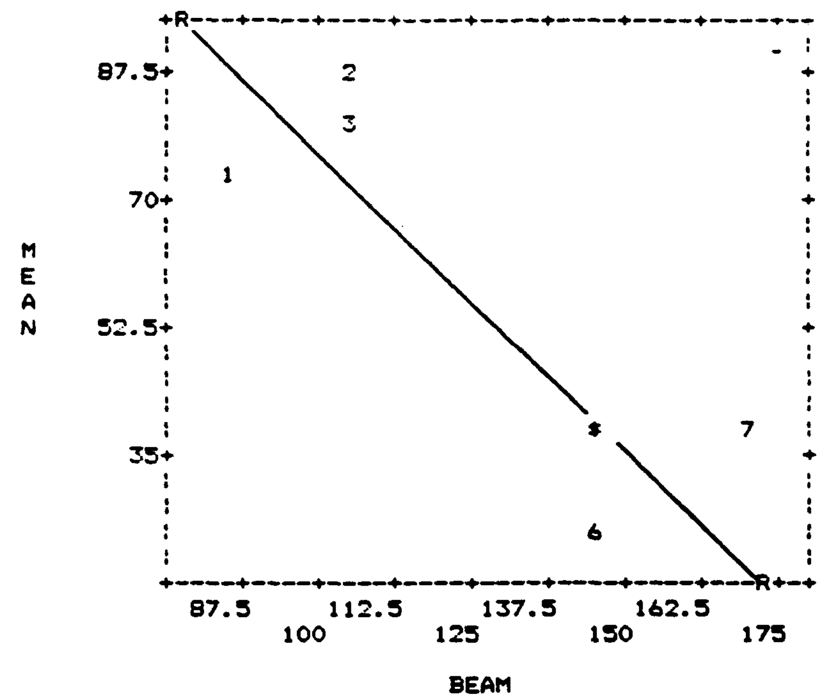


FIGURE 31. MN_0, BEAM, AND LINEAR MODEL IN TURN-ENTRY

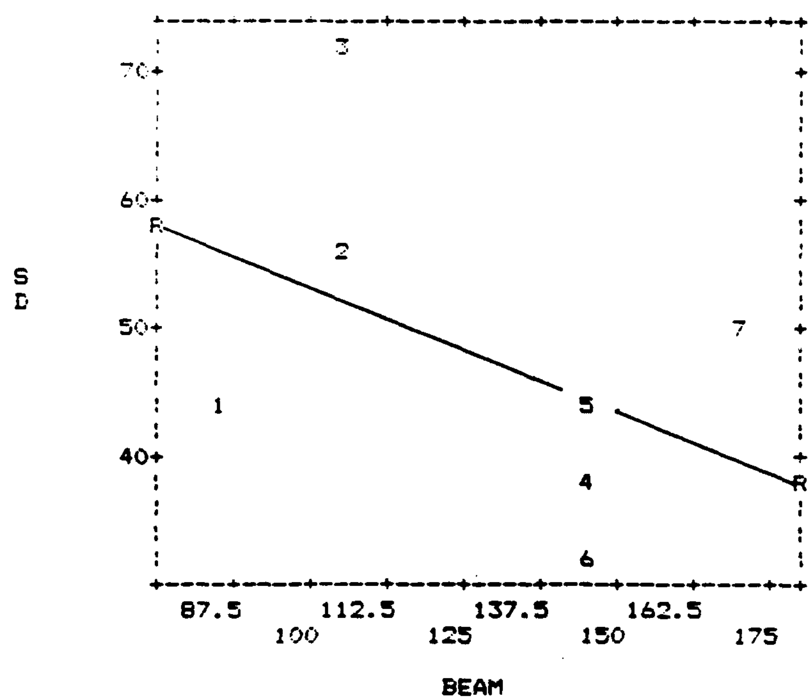


FIGURE 32. SD_0, BEAM, AND LINEAR MODEL IN TURN-ENTRY

TABLE 19. STATISTICS FOR MODELS IN TURN-ENTRY

REGION	STAT	MN= *f*(B)		SD= *f*(B)	
		C1	C2 B	C1	C2 B
	R	0.85		0.427	
	BETA	–	-0.85	–	-0.427
TURN	F	13.17		1.115	
-ENTRY	PR>F	0.0151		0.3393	
	t	5.57	-3.63	3.10	-1.056
	PR>|t|	0.0026	0.0151	0.0267	0.3393
	C1	148.49		71.69	
	C2	-.73403		-.18516	

4.3.2 Regression Models in the Trackkeeping Regions

The first step was a selection among the potential models (16) through (19). Correlation coefficients for the potential models with MN_0 and SD_0 presented in Table 20. Note that a distinction has been made between the two channel legs. The experimental channel was designed with a following current in Leg 1 that allowed the ship to maintain a position at the center of the channel and a heading parallel to the channel course. In Leg 2 the current had a crosstrack vector that made it difficult to maintain the ship at the exact center of the channel and that required several degrees of crab angle to maintain a track parallel to the channel course. (The channel is described briefly in Section 1.4 here and in greater detail in an earlier report, Smith et al., 1990.) The crosscurrent makes shiphandling relatively more difficult (Smith et al., 1985), a conclusion that is supported by the performance data presented here in Section 3.2, Table 9.

In Table 20 the MN_0 values for the first leg of the channel are not meaningfully correlated with any of the considered models. This lack of correlation reflects the pilot's success in maintaining the centerline of the channel in absence of any external disturbances, regardless of the ship's dimensions. Consequently, the MN_0 has been modeled as a constant parameter:

$$MN_0 = -4\ ft \qquad (31)$$

TABLE 20. CORRELATIONS FOR MODELS (16) TO (19) IN TRACKKEEPING

Waterway region:		TRACK-KEEPING			
No	f (I)	channel leg 1		channel leg 2	
		R(MN)	R(SD)	R(MN)	R(SD)
1	DISPL/10,000	0.08	0.81	0.82	0.47
2	LN(DISPL/10,000)	0.17	0.85	0.79	0.64
3	L	0.21	0.64	0.73	0.57
4	B	0.08	0.88	0.83	0.62

MN and SD are the Mean and Standard Deviation values for the position of the ship's geometric center.
R( ) is the correlation coefficient of ( ).
* is a notation for non-dimensional parameter.

DISPL is the ship's displacement [Long Tons].
L is the ship's length between perpendiculars [ft].
B is the ship's beam (molded) [ft].

The standard deviation, SD_0, is meaningfully correlated with the ship's beam in both legs of the channel. This selection is consistent with that in the turn-entry region. The scatter plot for the relation between the beam and SD_0 is shown in Figure 33. The plotting symbols for the ships are as follows:

1 33 k bulk carrier,
2 1000 ft Great Lakes carrier,
3 76 k bulk carrier,
4 150 k bulk carrier - original rudder,
5 150 k bulk carrier - degraded rudder,
6 150 k bulk carrier - upgraded rudder,
7 250 k tanker.
("$" represents the superposition of two ships.)

The results of the regression analysis, including the regression coefficients, are presented in Table 21. The intercept, 0.1, of the model (32) does not satisfy the significance requirement.

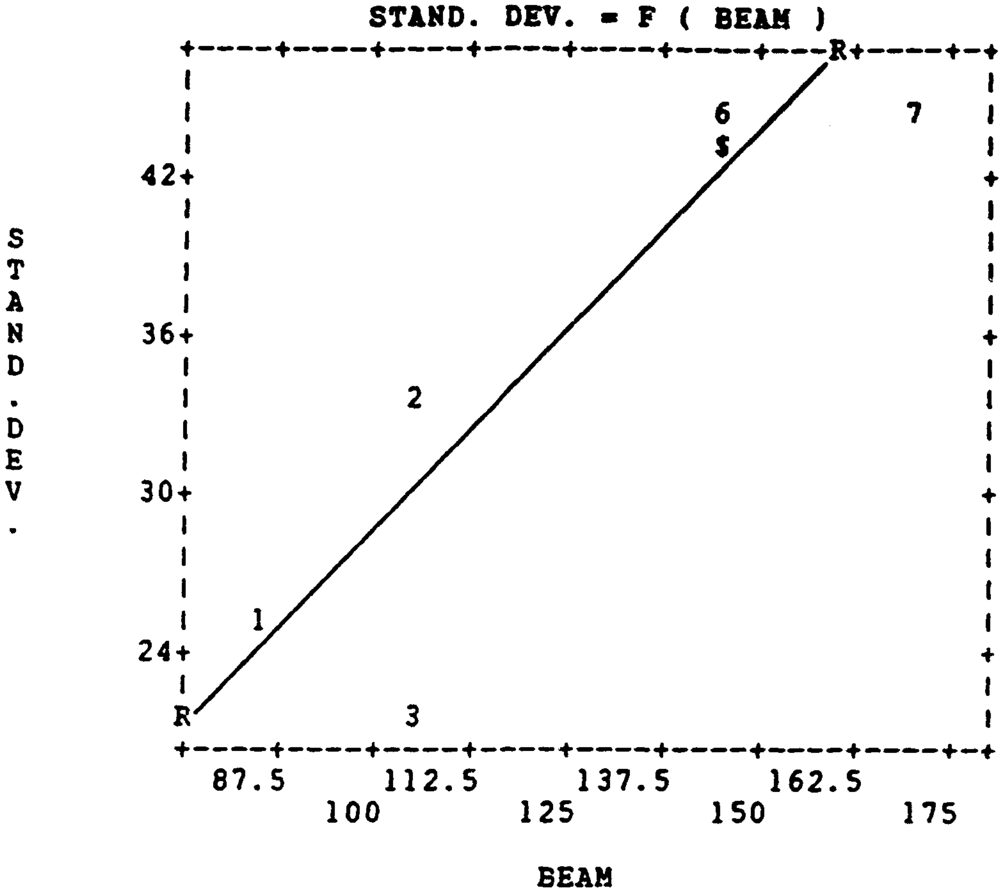


FIGURE 33. SD_0, BEAM, AND LINEAR MODEL IN TRACKKEEPING, LEG 1

However, it has not been removed from the model for consistency with the similar model selected for the second leg of the channel. The qualitative effects of that decision are negligible in this particular case. Thus, the SD_0 has been modeled as follows:

$$SD_0 = 0.1 + 0.28335 \cdot B \tag{32}$$

where: B is the ship's beam (molded) [ft].

The MN_0 and SD_0 values in Table 20 are better correlated with the ship's beam in the second leg of the channel. This effect can be explained by the presence of the water current acting across the channel leg. With the ship off the center of the channel and the bow of the ship presented at an angle to the channel edges marked by the buoys, the pilot needs to make a more difficult judgment about his crosstrack position, using the beam as a metric. The wider the beam, the wider his judgment as to what constitutes the "centerline." The scatter plots for these correlations are presented in Figures 34 and 35. The plotting symbols for the ships are as follows:

TABLE 21. STATISICS FOR SD_0 MODEL IN TRACKKEEPING, LEG 1

REGION	STAT	SD= *f* (B) C1	C2 B
	R	0.88	
Track-	BETA	–	-0.88
keeping	F	17.95	
Leg 1	PR>F	0.0082	
	t	0.011	4.237
	PR>|t|	0.9917	0.0082
	C1	0.09673	
	C2	0.28335	

1 33 k bulk carrier,
2 1000 ft Great Lakes carrier,
3 76 k bulk carrier,
4 150 k bulk carrier - original rudder,
5 150 k bulk carrier - degraded rudder,
6 150 k bulk carrier - upgraded rudder,
7 250 k tanker.
("$" represents the superposition of two ships.)

The statistics, including the regression coefficients, are presented in Table 22. The following models have been selected:

$$MN_0 = -30.4 + 0.41255 \cdot B \tag{33}$$

$$SD_0 = 20.8 + 0.13776 \cdot B \tag{34}$$

where: B is the ship's beam (molded) [ft].

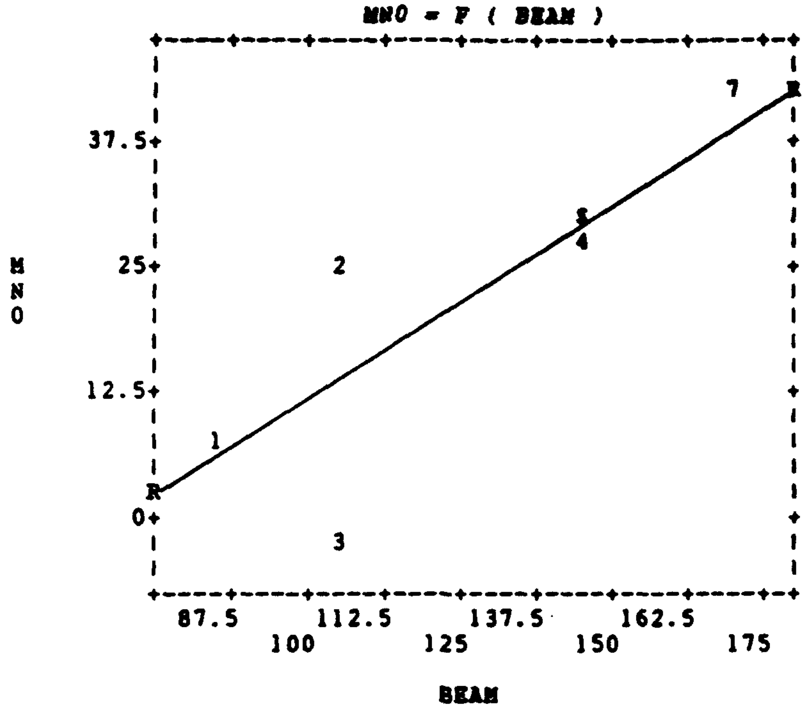


FIGURE 34. MN_0, BEAM, AND LINEAR MODEL IN TRACKKEEPING, LEG 2

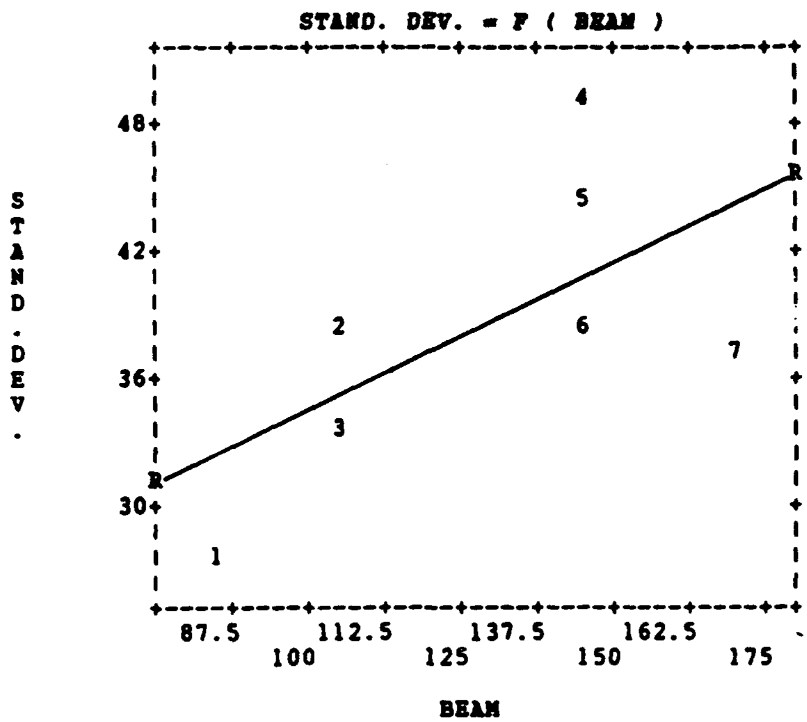


FIGURE 35. SD_0, BEAM, AND LINEAR MODEL IN TRACKKEEPING, LEG 2

TABLE 22. STATISTICS FOR MODELS IN TRACKKEEPING, LEG 2

REGION	STAT	MN= *f*(B)		SD= *f*(B)	
		C1	C2 B	C1	C2 B
	R	0.83		0.616	
	BETA	–	-0.83	–	-0.616
Track-	F	11.194		3.057	
keeping	PR>F	0.0204		0.1408	
Leg 2	t	-1.871	3.346	2.008	1.748
	PR>|t|	0.1202	0.0204	0.1009	0.1408
	C1	-30.39298		20.83764	
	C2	0.41255		0.13776	

4.4 FINAL FORMS OF THE SELECTED MODELS

Regression models selected in Sections 4.1 to 4.3 are presented below in a form useful for application:

- for the turn region:

$$MN_0 = -0.139 \cdot L + 0.041 \cdot D_T^* \cdot L$$

$$SD_0 = -75.9 + 0.053 \cdot D_T^* \cdot L$$

- for the turn-recovery region:

$$MN_0 = 158.0 - 65955.89 \cdot K^* \cdot 1/L + 0.02564 \cdot T^* \cdot L$$

$$SD_0 = 83.5 - 24932.73 \cdot K^* \cdot 1/L + 0.010058 \cdot T^* \cdot L$$

- for the recovery region:

$$MN_0 = -2.9 - 0.00467 \cdot T^* \cdot L$$

$$SD_0 = 28.7 - 5351.6 \cdot K^* \cdot 1/L + 0.00642 \cdot T^* \cdot L$$

- for the entry region:

$$MN_0 = -33.3 - 0.00413 \cdot T^* \cdot L$$

$$SD_0 = 28.5 - 4159.04 \cdot K^* \cdot 1/L + 0.00162 \cdot T^* \cdot L$$

- for the turn-entry region:

$$MN_0 = 148.5 - 0.734 \cdot B$$

$$SD_0 = 71.7 - 0.185 \cdot B$$

- for the trackkeeping region:

  - in Channel Leg 1:

$$MN_0 = -4 \text{ ft}$$

$$SD_0 = 0.1 + 0.28335 \cdot B$$

- in Channel Leg 2:

$$MN_0 = -30.4 + 0.41255 \cdot B$$

$$SD_0 = 20.8 + 0.13776 \cdot B$$

where:

MN_0, SD_0 [ft] are values of the Mean and Standard Deviation for the maximal crosstrack position of the ship's center of gravity,

K^*, T^* [-] are Nomoto's indices (nondimensionalized),

D_T^* [-] is the tactical diameter (nondimensionalized),

L [ft] is the ship's length between perpendiculars, and

B [ft] is the ship's beam (molded).

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5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 USCG EVALUATION OF PERFORMANCE IN RESTRICTED WATERWAYS

The USCG's Aids to Navigation Manual - Administration (COMMANDANT INSTRUCTION M16500.7) requires the use of a quantitative procedure for the evaluation of performance in restricted waterways. For a number of years such a procedure has been available, providing a measure of performance, or risk, in a subject waterway for given conditions of waterway configuration (including aids to navigation), ship characteristics, and environmental conditions (Smith et al, 1985). The basis of this procedure is a pool of data collected on real-time man-in-the-loop simulators since 1978. The general simulator methodology involves transits of a design harbor and the measurement of the precision of ship tracks in the channel.

Recently, the USCG has had a requirement to improve the accuracy of the procedures as they treat the contribution of ship characteristics to total performance and to extend the range of ship sizes to include the very largest commercial vessels. A dedicated simulator experiment was conducted to provide the necessary performance data (Smith et al., 1990). A novel aspect of this experiment was the selection of ship models along a number of physical dimensions and indices of inherent controllability. These parameters could potentially be used, singly or together, in regression formulas describing the relation between these ship parameters and the observed piloted performance. An earlier USCG study, describing a large sample of actual commercial vessels by similar parameters, provided the assurance that the experimental results would be representative of real world cases (Barr et al., 1981; Barr et al., 1989).

The present report has been a description of the development of the regression formulas. Because of the complexity of the problem and the general novelty of the approach, little direct guidance was available in the subject literature and every component of the development involved decisions about appropriate methods. Therefore, the conclusions are about the methods that were used in this study as well as about the actual results or findings. The conclusions that follow are divided into sections on the selection of ship parameters, the measurement of piloted performance, and the development of the regression models, but the division is entirely arbitrary. Conclusions about each component are based on its effectiveness in functioning with the others. A final view of the results of the reported study is in the following Section 6, which discusses their implementation in procedural computer software for the USCG waterway system designer.

5.2 CONCLUSIONS

5.2.1 Selection of Ship Parameters

The first and most obvious type of ship parameters to consider were physical dimensions. These have the advantage of being easily available to, and well understood by, the shiphandler who applies them and the system designer who will use the evaluation procedure. For this reason the ships' physical dimensions--length, beam, draft, and displacement--were considered at every step. Unfortunately, they were only modestly effective in describing piloted performance and, therefore, are not sufficient as a basis for the desired evaluations. But because the ease of use of the evaluation procedure was a major consideration in its development, provisions have been made for the use of such dimensions by the system designer. The implementation of the regression formulas in procedural software will allow the system designer to input only physical dimensions and have the software estimate other needed parameters. A description and test of this substitution are presented in Section 6.

The primary ship parameters considered were those derived from sea trials, especially the two most-commonly accepted standard maneuvers, the turning circle and zigzag. The specific "indices of ship inherent controllability" derived from these maneuvers that were considered during the design of the experiment and during the analysis were the following: tactical diameter, overshoot angle, time to reach the first execute heading change, course lag time, K and T (Nomoto's indices), and P (Norrbin's index). These indices were effective as indicated by their high correlations with measures of piloted performance. In addition, in preliminary tests, performance was greatly improved for ships representing favorable qualities of inherent controllability. As an example, reductions of up to 28% of the mean of crosstrack distances off the centerline and 46% of the standard deviation were observed for the same ship with an upgraded, compared to a degraded, rudder. The final selection of indices was made in conjunction with the development of the regression formulas. The selected indices are those that were the basis of the selected formulas, which are discussed below.

5.2.2 Measurement of Piloted Performance

Past methods of representing the piloted performance data measured on the simulator proved inadequate in the present analysis. In earlier data collections, each set of conditions evaluated was represented by examining the set of tracks made by multiple transits of the channel by the ship, measured at its center of gravity. Each transit was divided into "regions" based on the ship maneuver (for example, turn) required there. Within each region the cross section through the distribution of tracks that showed the highest risk was selected as representative. Risk

was indicated by the largest mean distance from the centerline, and/or the largest standard deviation, and/or the largest "relative risk factor." The last is a calculated index used in the waterway evaluation procedure. A preliminary analysis showed that representative data selected in this way was sensitive to differences in the ships' overall size, but did not sensitively reflect differences in controllability. (The preliminary analysis is reported in Smith et al., 1990.)

A new method of selecting the representative data was attempted, designed to be maximally sensitive to the underlying controllability of the ship. First, the set of transits was examined to identify the most common piloting technique for the required maneuver: that is, a characteristic pattern of crosstrack position, heading, and rudder angle. The minority of transits that did not show the characteristic pattern were discarded. Then each transit was examined individually for the highest risk in a maneuvering region. For an individual transit, this was the closest approach of an extreme point of the ship's contour to the channel boundary. The crosstrack position of the center of gravity was selected at this point. The means and standard deviations of these points proved quite sensitive to controllability.

A secondary objective of the experiment and analysis was to evaluate the effect of channel width on risk and performance and to improve the treatment of this effect in the waterway design procedures. Before this relation was established, and the primary regression formulas were developed, the performance data for the large range of ship sizes were transformed, based on a constant relative channel width. Two alternative approaches were considered: channel width relative to the length, or to the beam of the ship. The ship's heading relative to the channel course in a region was used as the deciding factor. In the turn, where this angle was large, length was used in the transform; in regions were the angle was small, beam was used. This distinction is consistent with pilot reports. Data treated in this way were successfully sensitive to indices of controllability logical for the maneuver. The established relation between channel width and performance showed that the pilots maintained a greater precision of tracks in wider channels and benefited more in decreased risk than had been hypothesized. (This matter is discussed further in Section 6, which follows.)

5.2.3 Development of Regression Models

The major effort in the analysis was the development of the regression models. A number of model forms were considered, based on one, or on combinations of two, indices. Selection of the final models, and their indices were based on a number of criteria. One of these was the correlation coefficient: the selected models correlated very highly with the representative piloted performance data. Another important criterion was the requirement that the

index or indices on which the model was based be meaningful for the requirements of the maneuvering region. A complete set of regression model is presented at the end of Section 4. A summary of the findings on the models and on the effectiveness of the considered ship parameters in their development follows:

1. The tactical diameter is a superior index of the ship's inherent controllability in the turn region where a steady hard rudder deflection is required. Linear relations between the tactical diameter and the mean and/or standard deviation were determined. A larger tactical diameter resulted in a mean track further to the outside of the turn, a larger standard deviation, and, therefore, would result in a larger calculated RRF.

2. Indices K and T, proposed by Nomoto, are the most effective in those regions where the rudder is used dynamically. Linear models of relations between K, T and mean and/or standard deviation are fully acceptable in the turn-recovery, recovery, and entry regions. The contribution of K becomes less significant for smaller amplitudes of rudder deflections.

3. Other indices investigated were less effective than those selected. The overshoot angle and the course lag time can be used as a replacement for K and T, however, with a noticeable loss of accuracy. With these indices also, linear models are acceptable in the turn-recovery, recovery, and entry regions. Index P, proposed by Norrbin, and the "time to reach the first execute heading change" were considerably less useful than the above mentioned parameters in all regions.

5.3 RECOMMENDATIONS

5.3.1 Application to the Waterway Design Procedure

The application of the findings to the U.S. Coast Guard's Waterway Design and Analysis Project, the objective of this study, is discussed in some detail in Section 6, which follows.

5.3.2 Prediction from Ship Physical Dimensions

The full use of the relations developed here depends on the availability of indices of ship inherent controllability for the subject ships. These values are not readily available and are difficult to calculate by all but the most-sophisticated system designer. The procedure is presently being implemented providing estimates for the designer with incomplete information on the ship of interest. (See Section 6.) The most accurate predictions from the more-readily-available physical dimensions of the ship (length, beam, draft, etc.) would require the development of statistical relations between these dimensions and the indices on which the regression models are based. The U.S. Coast Guard has the required

data available (Barr et al., 1981, Barr et al., 1989).

5.3.3 Additional Applications of the Prediction Formulas

The findings of the reported investigation have implications for shiphandler training and for bridge operations. The commercial pilots who participated in the simulator experiment are among the most sophisticated and highly trained of shiphandlers. As pilots associated with a harbor, rather than a single ship, they frequently encounter new ships and are the most likely to encounter ships that are sufficiently strange to them to affect shiphandling. Yet they are not in the habit of considering any ship inherent controllability parameters of the type that were demonstrated here to predict ship performance. The findings suggest that a greater emphasis in their training on the description and prediction of ship inherent controllability would contribute to the safety of transits, especially in the high-risk narrow channel situation, and most especially with larger ships. In order for this training to transfer to the operational situation, appropriate information and the opportunity to study it would have to be available on the bridge of a ship. Note that S.N.A.M.E. has recommended that the zigzag maneuver, as well as the turning circle be posted (Landsburg et al., 1980).

Another potential use of the present findings is in the development of steering displays. An earlier U.S.C.G. study found that the most effective display for the control of deep-draft ships in restricted waterways in severely-reduced visibility was a "predictor steering" display that showed the ship's true position along with a prediction of position three minutes into the future (Cooper, Marino, and Bertsche, 1981). At the time this display was disregarded as impractical and costly because it required a full hydrodynamic model for each ship and a computer capable of running it. Such a display could be developed using Nomoto's simple model (one equation for equivalent yaw motion) (Nomoto, 1966). Its space and time requirements are minimal, and it is uniquely determined by the K and T coefficients.

5.3.4 Investigation of Additional Conditions

The work carried out in this project has resulted in several developments that are new in this field. However, in order to complement the established results, the following areas can be recommended for further investigations:

1. The effect of a limited alongtrack length for a region should be investigated. The regions in the present experiment were not limited; the pilots could complete a specific maneuver at any point along the waterway. As an example, it is reasonable to believe that the physically-limited length of the turn-recovery region would create a more-stressful situation in the following recovery region. Such an effect cannot be predicted theoretically

because of the need to include the performance of the pilot. One immediate application of such an investigation would be in the selection of sites for anchorages or docks alongside the waterway.

2. The effect of the channel width should be investigated further. In the present analysis, the linear models for relations between the relative width and the mean and standard deviation had to be accepted. It is reasonable to believe that the relations have an asymptotic (nonlinear) character. The pilot cannot improve the quality of shiphandling to zero values of mean and standard deviation. The question is, what are the boundary values for the mean and standard deviation? Can that boundary be associated with the same relative width of the channel for all the ships? Answers to these questions are important for the waterway designer and the operator.

3. Transits of ballasted tankers in the presence of wind should be investigated. Although the inherent maneuverability is improved in the ballast condition, the wind lateral force becomes disproportionately greater. It makes shiphandling significantly more difficult and risky. (Pilots participating in the experiment reported that they consider the control of a large tanker or bulk carrier in ballast in the presence of wind far more difficult than that of the same ship fully loaded. "She's like a balloon in the water.") The results of such an investigation would have consequences for operational practice in the handling of large ships.

6.0 APPLICATION TO THE WATERWAY DESIGN MANUAL

6.1 BACKGROUND

The objective of the Ship Performance experiment (Smith et al., 1990) and the analysis reported here was the development of a new procedure for the USCG'S use in predicting performance and risk in restricted waterways. The final step in this development is the incorporation of the findings into the revision of the Design Manual (Smith et al., 1985) and its supporting Automated Relative Risk Factor (ARRF) software ("User's Manual...," 1988). As of this writing, the revisions of both are in preparation. This section discusses the changes to the design process resulting from incorporation of the new work. For the sake of brevity, it is assumed that the reader is familiar with the experiment, the Design Manual, and the software.

6.2 SHIP SIZES TO 250,000 DEADWEIGHT TONS

A major objective was to increase the range of ship sizes that could be considered by the design process. The experiment and the analysis included ships to 250,000 dwt. Compared to the existing process, the lower end of the new range is approximately the same: 30,000 dwt versus 33,000 dwt. There is now no practical upper limit, given that ships the size of the upper end of the new range, the 250,000 dwt ship, do not now make narrow-channel transits under their own power. (The selection of the ships for inclusion in the experiment is discussed in Smith et al., 1990.)

6.3 SHIP PARAMETERS INCLUDING SIZE AND CONTROLLABILITY

The change from the earlier, single parameter of deadweight tonnage, a parameter most appropriate in comparing similar tankers, to the several parameters of size and controllability means more effective prediction for a greater variety of ships. However, to take full advantage of the sensitivity and accuracy of the new predictions, the system designer should have more information available on the characteristics of his design vessel. Ideally, the following parameters should be available for the specific ship:

- displacement (and/or deadweight tonnage)
- length, beam, and draft
- nondimensional tactical diameter
- K* (the Nomoto index for turning ability)
- T* (the Nomoto index for quickness of response to steering)

These include the parameters that were found to be effective in the analysis discussed in Section 4, those that are needed to calculate the positions of the extreme points of the ship contour as

discussed in Section 3.2, and those needed to estimate any parameters not entered by the system designer.

The revised Manual will include guidance on the parameters needed. These parameters will vary in the ease of their availability for a specific ship. The physical dimensions should be readily available from published references. The USCG requires that turning circle data for a vessel, or for the first vessel of its class, be posted on its bridge. Therefore, with some greater effort, the tactical diameter should be available. Because the zigzag maneuver is not required by the USCG, such a test may never have been done or the data may not be available. To ensure the maximal usefulness of the new procedures, the revision of the software to incorporate the formulas described in Section 4 also included routines to estimate missing parameters from those that are entered by the system designer. These routines were designed assuming that the typical user will have the physical dimensions of the subject ship, but is less likely to have its indices of controllability. The methods of estimation may not need to be exactly accurate. The estimated indices are to be used only by the software in calculating the relative risk factor (RRF). What is important is the degree of sensitivity of the RRF to small differences in index values and the resulting similarity of RRF values calculated with varying amounts of input. Preliminary tests to test the effect of estimated indices on the RRF are discussed below.

A sample of data from preliminary tests is presented in Figure 36. Calculations of RRF done by entering all the parameters listed above for the subject ships are compared with calculations done using only the more-readily-available physical dimensions. These data represent the turn-recovery region, the region that resulted in the highest values of the RRF, or the greatest risk. It corresponds closely to what was called the "turn" or turn pullout in the earlier Design Manual and software. For the purposes of this sample, this region was described as a three-buoy noncutoff turn in daylight with no crosscurrent. Channel width was entered as a constant and arbitrary 350 feet. This is unrealistic for the larger ships but necessary for a measurable risk with the smallest ship. The ships used were those used in the experiment and the analysis, ships for which all parameters were available. They are numbered as follows:

1 33 k bulk carrier,
2 1000 ft Great Lakes carrier,
3 76 k bulk carrier,
4 150 k bulk carrier - original rudder,
5 150 k bulk carrier - degraded rudder,
6 150 k bulk carrier - upgraded rudder,
7 250 k tanker.

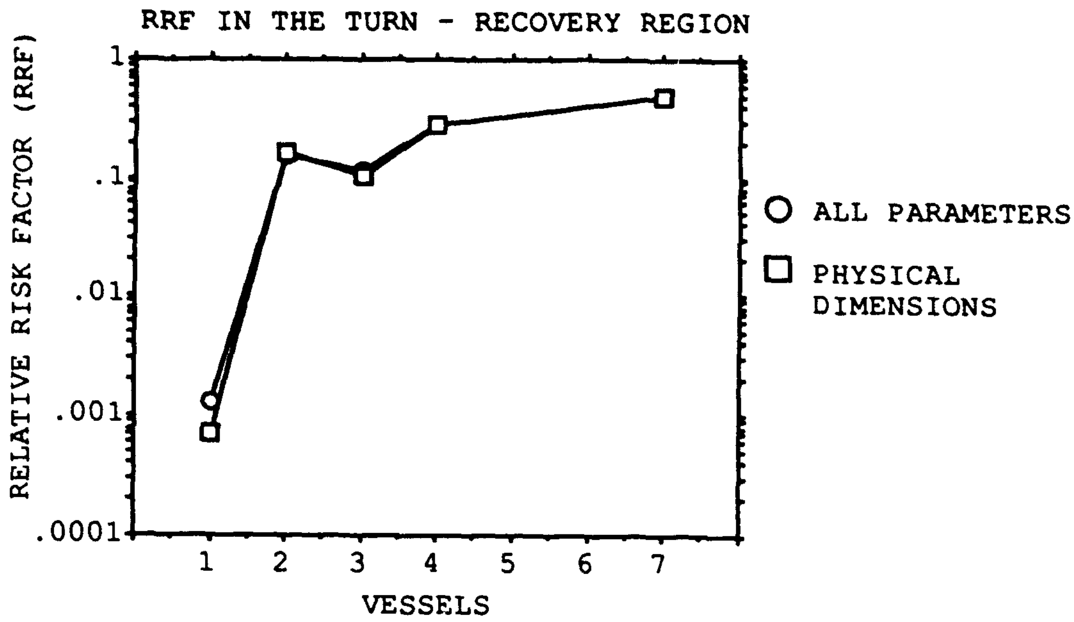

FIGURE 36. ALL PARAMETERS V. PHYSICAL DIMENSIONS ONLY

Parameters values for these ships were taken from Appendix A here. Ship speed was entered as 9 knots. In the figure the ships are presented as an ordinal scale by displacement, with an arbitrary order for the additional 150k bulkers. No data are plotted in this figure for Ships 5 and 6, the 150k bulkers with modified rudders. Physical dimensions alone cannot describe such differences. RRF is plotted as a multi-cycle logarithmic scale, as it was in the 1985 Design Manual in data plots and in the "totem pole." The two functions are very similar, even overlaid for the larger ships. (The inversion in RRF between Ships 2 and 3 is the result of the a-typical length of the 1000-ft ship.) Calculations for other sets of conditions show similar results. These tests support the use of the software, with designer-entered physical dimensions and software-estimated controllability indices, for the anticipated typical use of the software: the evaluation and design of waterways for ships differing in size and resulting controllability.

A less-typical, but potential, use considered was the evaluation of ships that differed only in controllability, as was the case for the three 150k bulk carriers included in the experiment and the analysis. Obviously, physical dimensions alone are not sufficient to describe the differences between or among such ships. The use of the Nomoto parameters, calculated from the zigzag maneuvers would make the best use of the present findings, now incorporated into the software. But they may not be available.

Tests of the software were done to determine whether the physical dimensions and the nondimensional tactical diameter, along with software estimates of the Nomoto indices would be adequate for such a use. Sample data are presented in Figure 37. In that figure, data are presented for Ships 5 and 6. Note that the RRF is plotted on a linear scale to increase the vertical resolution of the relatively-high RRF values. (The absolute values presented are high because channel width was 350 feet for these large ships.) The RRF calculated with all parameters reflects the variations to be expected with rudder changes. Ship 5 with a degraded rudder yields a higher risk than Ship 4; Ship 6 with an upgraded rudder yields a lower risk. Unfortunately, the incomplete set of parameters does not result in a sensitivity of the RRF to ship controllability. For this type of use, the Nomoto indices for the subject ships are essential.

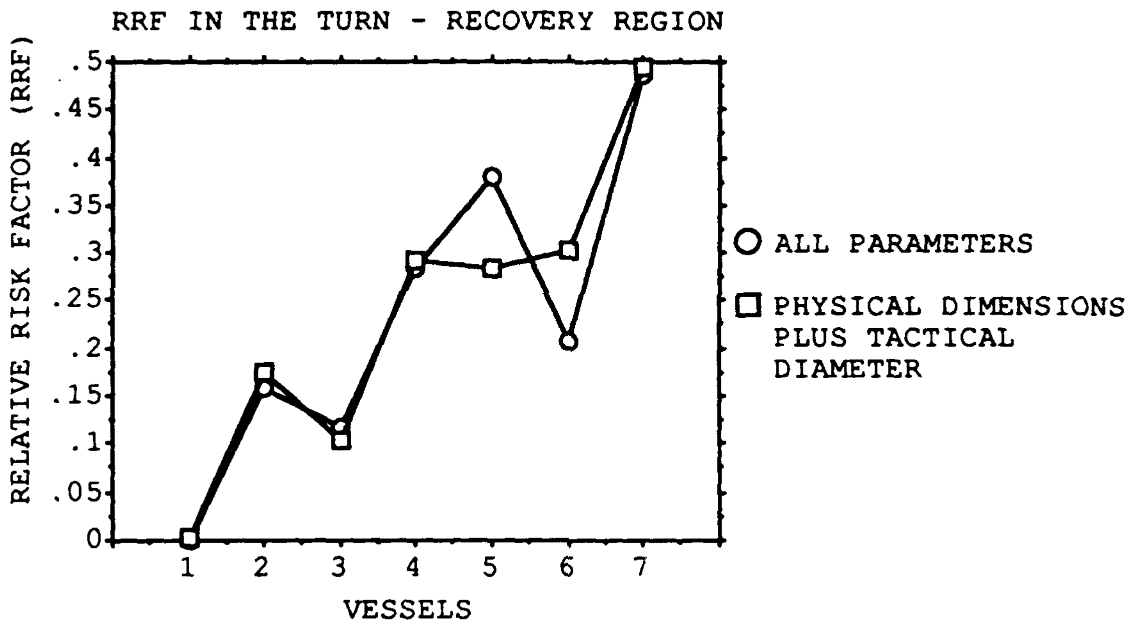

FIGURE 37. ALL PARAMETERS V. PHYSICAL DIMENSIONS PLUS TACT. DIA.

6.4 WATERWAY REGIONS

The waterway was divided into regions based on the constituent maneuvers required for a transit of a narrow channel. The transit requirements are described briefly here in Section 1.4.2. To ensure a maximum sensitivity of the piloted performance to the controllability indices, a more painstaking procedure was used for this data analysis than was used in the earlier experiments on which the 1985 Design Manual was based. This data analysis procedure is described briefly here in Section 3.2. This new procedure resulted in differences with the previous regions on which the existing Design Manual and software are based. The previous and new regions are listed below, in an order that physically mimics their place in the up-bound experimental transit illustrated in Section 3.2 of this report.

<u>Previous</u>	<u>New</u>
trackkeeping with crosscurrent	trackkeeping (Leg 2)
recovery with crosscurrent	recovery
turn	turn-recovery
	~~turn~~
	~~turn-entry~~
trackkeeping without crosscurrent	trackkeeping (Leg 1)
recovery without crosscurrent	entry

The principal differences are in the critical turn. In the existing Manual process, the turn is represented by performance measured several ship lengths beyond the turn apex, where the risk was measured as greatest in earlier experiments. In the new analysis the turn is divided into "turn-entry," "turn" and "turn-recovery" regions. (The earlier regions are treated in the Design Manual in Sections 3, 4, and 5. The new treatment is discussed in the experimental report in Section 4 and in the present report in Section 3.2.)

For the revision of the Design Manual and software, some decisions were made about the incorporation of the new regions, especially the turn-associated regions. The intention was to maximize the quality of the new predictions while minimizing the disruption to the existing procedure. Preliminary calculations of RRF values, or risk, in these three turn regions identified the turn-recovery region as having the highest risk. This region, characterized by a maximal crosstrack distance of the ship's extreme point from the channel centerline several ship lengths beyond the turn apex (Figure 7), is the most comparable to the existing treatment in the Design Manual and software. For these reasons, the turn-recovery region alone was incorporated into the revised software as a replacement for the previous "turn." The other regions were replaced as indicated in the list above.

The ship's size and controllability influence not only the crosstrack distance required by each maneuver but the alongtrack distance as well. The present Design Manual recommends that the "turn region" be 0.50 nautical miles in each direction from the turn apex, a distance that was "conservative" for then-existing ship performance data. That is, for the range of ship sizes in the earlier experiments, that distance enclosed all the turn maneuvers. The Design Manual also specifies different lengths for the "recovery region," based on the ship size. (The lengths of the existing regions are described in Section 3.3 of the Design Manual.) Because of the greater range of ship sizes treated by the revised procedures, it will be inappropriate to specify a single value for any region. For the Manual revision, the length of each region will be specified for the design vessel, based on the average alongtrack distance used by the experimental ships. When the revisions are complete, it may be that the original divisions remain appropriate for the smaller ships in the range, ships comparable in size to those included in the 1985 Manual.

6.5 CALCULATIONS OF THE RELATIVE RISK FACTOR (RRF)

The primary effect of the Ship Performance efforts on the design and evaluation process will be in the procedures for calculating the RRF. The existing ship size and channel width "correction factors" will be replaced by the implementation of the new formulas that have been the focus of this report. The "adjusted beam" will be replaced by a more-complete calculation of the ship's "extreme points." This new calculation is based not only on the length, beam, transit speed of the ship, and the crosscurrent velocity as before, but also includes the crab angle resulting from the required maneuver in the region. The intention is to implement these changes only in the supporting software and not to provide anything like the "worksheets" in the 1985 Manual. Therefore, these changes will be apparent to the system designer only in terms of the differences in input data--the ship parameters discussed in 6.3 above--and in the output. (The existing procedures are presented in the 1985 Design Manual in Section 5 in the worksheets. The existing software corresponds closely to those worksheets.)

The new output and its differences from those of the existing Manual procedures are a major concern to the system designer and require some preview here. A sample of preliminary test data comparing old and new calculations in the turn-recovery region is presented in Figure 38. Conditions represented are a three-buoy noncutoff turn in daylight with a 350-foot channel width. The three smallest experimental ships, those within the range of the old software, are included:

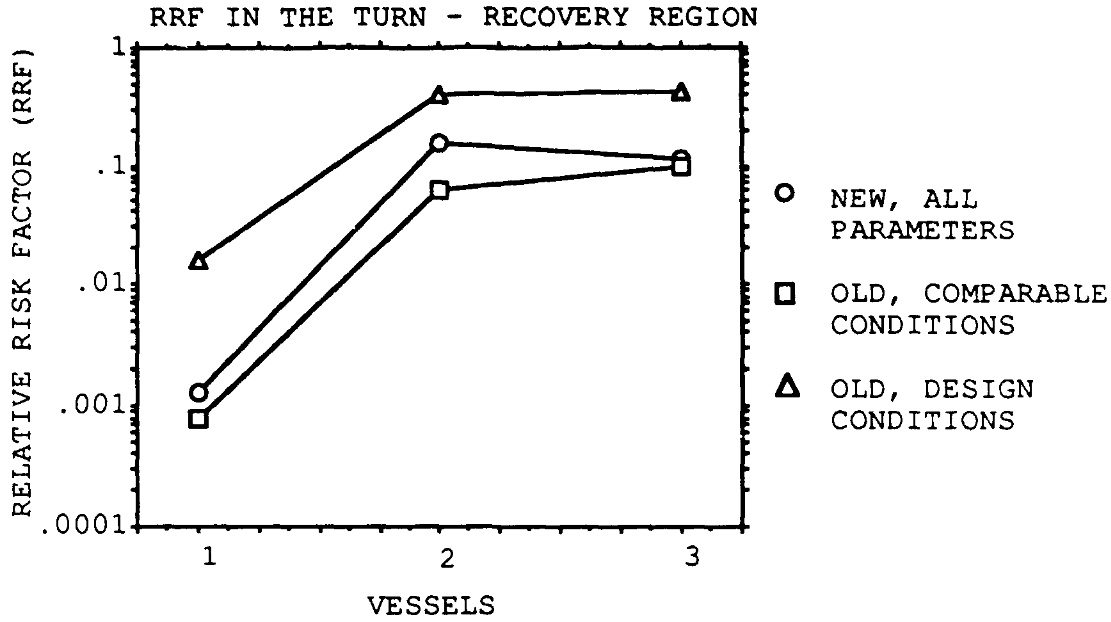

FIGURE 38. RRF USING OLD AND NEW SOFTWARE

1 33 k bulk carrier,
2 1000 ft Great Lakes carrier (66 k),
3 76 k bulk carrier.

Three functions are plotted. The first, indicated by circles, represents the RRF calculated with the newly-revised software with no crosscurrent and a transit speed of 9 knots. The second, indicated by squares, represents the old software with the same zero current and 9 knots transit speed. With these conditions, RRF values are higher with the new version. This difference is at least partially the result of the way the two versions deal with the ship's crab angle in the channel. In the old version, crab angle was only the result of a crosstrack current component. With zero current entered, as was the case here, the "adjusted beam" would be only the entered beam of the ship. In the new version, the "extreme points" of the ship's contour are calculated, assuming a crab angle attributable to the maneuver in that region. For the turn-recovery, illustrated in Figure 7, the average crab angle in the experiment was - 5.9 degrees (to the left of the channel course). Values for crab angles in other regions are presented in Table 12.

The existing Manual and software recommend the use of "design conditions" to obtain a "conservative" measure of risk, meaning that if the measurement erred, it erred in the direction of over-estimating risk and encouraging caution. The third function in

Figure 38 was calculated by the old software using the design conditions of 0.50 knots of crosscurrent and a relatively-slow transit speed of 6 knots. These conditions are indicated by the triangles. With the recommended design conditions, the old version is substantially more conservative than the new. As assumed, the old design conditions produces very conservative results, more conservative than the more realistic conditions possible with the new version. The new Manual and software will treat the general level of the RRF differently. Because the new procedure treats the ship's heading and contour more realistically, less artificiality will be introduced. The recommended design speed will be 9 knots with an actual crosscurrent. The system designer will be advised that the new values are less conservative than the old. Artificial crosscurrent will be suggested only if the system designer believes that an extra conservatism is needed in the particular case.

6.6 CHANNEL WIDTH

An additional, major change in the Manual procedures is in the treatment of channel width. In the existing Design Manual and software, the "baseline" performance, represented by a mean and a standard deviation, is "corrected" for the subject channel width by an arbitrary straight-line function. This function was designed to ensure that those parameters increased more slowly than did the channel width and therefore, that the resulting RRF always decreased as the width increased. This function is replaced in the new software by formulas developed from the empirical performance data and presented in Section 3.3 of this report.

The new formulas representing the effect of channel width are a consideration in the differences in RRF values between the earlier procedures and the new revision. A sample comparison is presented in Figure 39. These results were calculated for the mid-sized ship, the 76,000 dwt bulker in several widths of channel. Conditions were the three-buoy noncutoff turn in daylight with zero crosscurrent and a 9-knot transit speed. The old version of the software shows a decrease in RRF with increased channel width. The new software also shows such a relation, but with a more pronounced drop. For the 250- and 350-foot channels, which are every narrow for the 76,000 dwt ship, the new function shows higher risk than the old. Note that the multi-cycle logarithmic scale minimizes the apparent difference between the two functions. For the wider channels, there is a cross-over, with the new function showing lower risk for the wide channels. The test calculations support the conclusion that for narrow channels, the new empirically-based function is more conservative than was the old function; while for the wider channels the new function shows lower, presumably more realistic, risk. Apparently, the pilots cannot increase precision

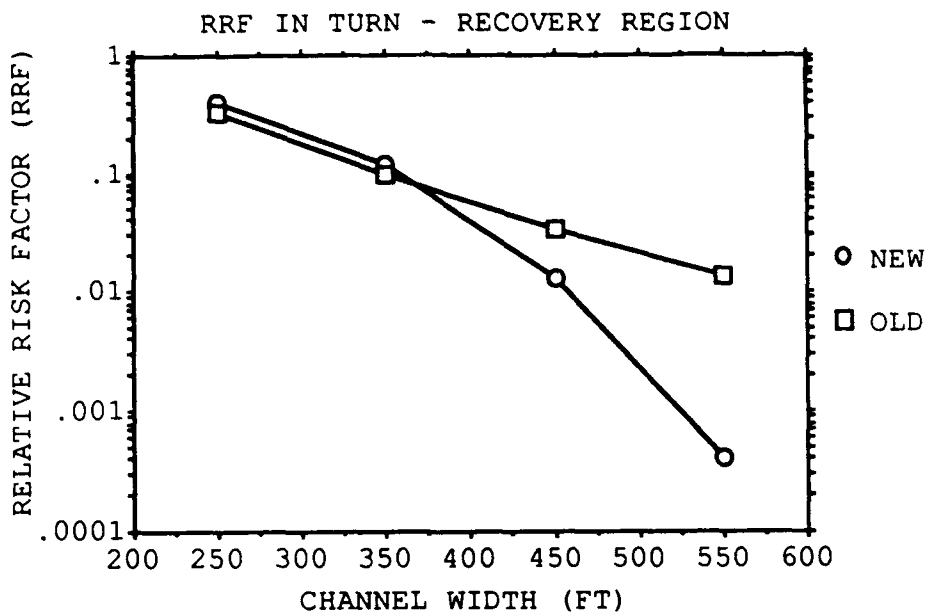

FIGURE 39. RRF FOR CHANNEL WIDTH IN OLD AND NEW SOFTWARE

in the narrow channels as much as was "hypothesized" by the old function but they can maintain a greater *precision* in wide channels. The new function represents a desirable combination for the purposes of the application: conservative in very narrow channels and more realistic in wider channels.

6.7 ANTICIPATED CONSEQUENCES OF THE APPLICATION

There are a number of consequences to the USCG district system designer, or other user of the Manual process, of the application of the new procedures. The major consequences are the increased capabilities that were the primary objectives of the Ship Performance efforts: it will be possible to consider a greater range of ships and to consider them with the greater generality and sensitivity allowed by the several parameters of size and controllability included in the new procedures. This greater sensitivity will mean that management decisions based on the characteristics of user traffic can be more strongly justified.

There is an unavoidable negative consequence to these changes in procedure in that waterway analyses made by the old procedures will not be comparable to those made by the new. The factors that contribute to this lack of comparability have been discussed above. These included the following changes (not necessarily independent of each other):

- the replacement of the ship size correction factor based on deadweight tonnage with the new formulas based on several parameters of ship size and controllability
- replacement of the adjusted beam with the calculation of the extreme points of the ship's contour, including region-specific crab angle
- the replacement of the nominal channel width correction factor by new formulas based on the empirical effect of channel width

How the general level of RRF values obtained with the revised ARRF software compare with those from the old version will depend on the trade-off among the effects discussed in the preceding subsections. For larger ships, of course, no comparisons will be possible. With smaller ships, the level will be generally lower with the revised version using realistic speed and current than with the old version using the generally-recommended "design" conditions. With extremely-narrow channels the new version will yield higher levels, but with medium or wide channels for the ship size the new version will yield lower levels. The generally-lower levels will look more realistic than did the old. However, they do add to the complexity of application. As was the case with the original version, low levels of RRF values, at or near 0.0000, mean a lack of resolution among conditions. For the older version this problem was solved by the "design" speed and current conditions that artificially increased RRF values.

In using the ARRF software for waterway management, the system designer who analyzed a channel in the past, or who has available to him earlier analyses, may want to examine the effects of changes over time by comparing successive analyses. Such comparisons will not be valid if different versions of the procedures have been used. He will, of course, have the option of continuing to use the original procedure, which will not be inappropriate if only smaller ships are involved and ship characteristics are not a major consideration for his situation. If the USCG requires uniformity across all analyses, re-analysis of old conditions of concern will be necessary.

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APPENDIX A

Potential Indices of the Inherent Controllability for Ships in the Experiment.

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NO	SHIP	DISPLacement	LENGTH	BEAM	DIAMeter	the first OVSHoot 10	15	20
		[LT]	[ft]	[ft]	[ft]	[deg]	[deg]	[deg]
1	33 k	42,072	574	85	2200	5.0	7.5	10.0
2	1000 ft	77,500	990	105	3160	3.3	5.1	6.8
3	76 k	86,174	855	106	2860	4.5	7.0	9.2
4	150 k	171,240	915	145	2540	5.7	8.8	12.3
5	150 k, degr. rud.	171,240	915	145	2780	7.2	11.2	14.8
6	150 k, upgr. rud.	171,240	915	145	2180	4.4	6.9	9.6
7	250 k	282,924	1085	170	2870	5.6	8.7	11.8

NO	SHIP	time to reach exec. heading change 10	15	20	course lag time (first oversh) 10	15	20	(acc.to Nomoto 10	15	20
		[s]	[s]	[s]	[s]	[s]	[s]	[s]	[s]	[s]
1	33 k	69	71	74	43	44	45	65	61	57
2	1000 ft	137	138	138	60	60	60	76	74	72
3	76 k	101	104	107	68	69	69	120	108	96
4	150 k	104	106	110	76	79	84	142	137	129
5	150 k, degr. rud	117	120	123	108	112	115	229	206	183
6	150 k, upgr. rud	88	90	93	48	51	54	76	77	76
7	250 k	123	126	130	90	94	98	170	164	154

NO	SHIP	K 10	K 15	K 20	T 10	T 15	T 20
		[1/s]	[1/s]	[1/s]	[s]	[s]	[s]
1	33 k	0.046	0.038	0.032	107	95	84
2	1000 ft	0.016	0.015	0.015	116	111	105
3	76 k	0.037	0.030	0.024	229	191	162
4	150 k	0.047	0.039	0.032	320	297	282
5	150 k, degr. rud.	0.134	0.083	0.059	1288	860	665
6	150 k, upgr. rud.	0.030	0.027	0.024	124	126	125
7	250 k	0.041	0.034	0.028	396	369	345

NO	SHIP	NON-DIMENSIONAL PARAMETERS					
		the first overshoot angle			time to reach exec. heading change		
		10	15	20	10	15	20
1	33 k	0.5	0.5	0.5	1.827	1.880	1.959
2	1000 ft	0.33	0.34	0.34	2.104	2.119	2.119
3	76 k	0.45	0.47	0.46	1.796	1.849	1.902
4	150 k	0.57	0.59	0.62	1.728	1.761	1.827
5	150 k, degr. rud.	0.72	0.75	0.74	1.944	1.994	2.043
6	150 k, upgr. rud.	0.44	0.46	0.48	1.462	1.495	1.545
7	250 k	0.56	0.58	0.59	1.723	1.765	1.821

NO	SHIP	NON-DIMENSIONAL PARAMETERS					
		course lag time (first overshoot)			(according to Nomoto)		
		10	15	20	10	15	20
1	33 k	1.138	1.165	1.191	1.721	1.615	1.509
2	1000 ft	0.921	0.921	0.921	1.167	1.136	1.106
3	76 k	1.209	1.227	1.227	2.133	1.920	1.707
4	150 k	1.262	1.312	1.396	2.359	2.276	2.143
5	150 k, degr. rud.	1.794	1.861	1.911	3.804	3.422	3.040
6	150 k, upgr. rud.	0.797	0.847	0.897	1.263	1.279	1.263
7	250 k	1.261	1.317	1.373	2.381	2.298	2.158

NO	SHIP	NON-DIMENSIONAL PARAMETERS					
		K*			T*		
		10	15	20	10	15	20
1	33 k	1.720	1.447	1.195	2.823	2.523	2.225
2	1000 ft	1.049	1.002	0.947	1.781	1.708	1.616
3	76 k	2.094	1.664	1.331	4.077	3.402	2.871
4	150 k	2.816	2.321	1.940	5.310	4.927	4.678
5	150 k, degr. rud.	8.086	5.012	3.523	21.389	14.289	11.048
6	150 k, upgr. rud.	1.794	1.632	1.445	2.062	2.095	2.083
7	250 k	2.899	2.399	1.982	5.553	5.162	4.832

NO	SHIP	NON-DIMENSIONAL PARAMETERS					
		P			AVERAGE		
		10	15	20	K*	T*	P
1	33 k	0.272	0.252	0.232	1.458	2.524	0.252
2	1000 ft	0.246	0.243	0.241	0.998	1.699	0.244
3	76 k	0.237	0.222	0.207	1.713	3.474	0.222
4	150 k	0.249	0.220	0.193	2.378	4.994	0.221
5	150 k, degr. rud.	0.186	0.171	0.155	6.444	16.219	0.171
6	150 k, upgr. rud.	0.373	0.334	0.297	1.620	2.073	0.335
7	250 k	0.246	0.218	0.192	2.441	5.193	0.219